THE DISTRIBUTION OF DAMS IN COSTA RICA

AND THEIR HYDROLOGIC IMPACTS

A Thesis

by

LAURA RICHARDS LAURENCIO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Geography

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Approved by:

Chair of Committee, Anne Chin
Committee Members, Hongxing Liu
Bradford Wilcox
Head of Department, Douglas Sherman

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ABSTRACT

The Distribution of Dams in Costa Rica

and Their Hydrologic Impacts. (December 2005)

Laura Richards Laurencio, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Anne Chin

Dam construction has increased exponentially over the past century, primarily in temperate environments. While the impacts of dams in temperate regions have been well-documented, a parallel level of research on dam impacts has not been achieved in tropical environments. The overall objective of this research was to understand the hydrologic impacts of dams in Costa Rica, a representative case study in a tropical environment. To achieve this objective, the following specific objectives were developed: 1) examine the spatial and temporal trend of large dam development within the country; 2) assess large-scale hydrologic impacts (at the national scale); 3) analyze downstream flow of individual dams to determine regional impacts.

Analysis of the spatial trend of dam development utilized a geographic information system. The spatial distribution showed no apparent relation to hydroclimate, and additional land-use analysis indicated that basins containing large dams are primarily covered by either forest or crop.

Assessment of large-scale impacts used potential reservoir storage to represent the hydrologic impact. Results indicate that large dams in Costa Rica are having a relatively low impact on the surface water component of the hydrologic cycle compared to temperate regions. However, this analysis revealed that two dams, Arenal and Sandillal, are having a disproportionately significant impact on their individual basins.

Analysis of flow regime for individual dams followed standard hydrologic analyses of comparing pre- and post-dam discharge data. Variables analyzed included mean, minimum, and peak flows. Results of these analyses revealed that the Arenal-Corobicí-Sandillal dam project have resulted in severe disruption to downstream hydrology for all three dams. In contrast, downstream of Ventanas Dam changes in downstream discharge were smaller than those documented for dams in temperate regions.

The results of this research indicate that dam impacts in the tropics may be very different from those documented in temperate environments. Consequently, theories developed for temperate areas regarding expected dam impacts may not apply to tropical regions. This has important implications for hydrology, geomorphology and ecology. This study should serve as a step toward development of a more generalized theory of dam impacts in the tropics.

DEDICATION

To my husband, David Laurencio,

my parents, David and Margie Richards,

and my mother-in-law, Dalia Edelman

ACKNOWLEDGEMENTS

This thesis could not have been completed without the assistance and support of a number of people who deserve my gratitude. I would first like to thank my advisor, Dr. Anne Chin, for providing continual feedback, guidance, and encouragement during this process. She has spent countless hours helping me with this research. Thank you for being a mentor, encouraging me to strive for excellence in my work. I am grateful to my committee members: Dr. Hongxing Liu and Dr. Bradford Wilcox for the educational enlightenment, advice, and support throughout my graduate career. I'd like to give a special thank you to Dr. Liu, for teaching me GIS, and patiently continuing to answer my questions. His feedback and encouragement have been greatly appreciated. In addition to my committee, I must extend my gratitude to Dr. Igor Vojnovic, who introduced me to the discipline of geography, and convinced me to continue my education and pursue this research. I would also like to thank my friends and colleagues in the Department of Geography that have supported and assisted me during this endeavor, most notably, José Gavinha, Wendy Patzewitsch, Jean Ellis, Marisa Rivera, and Barry Priest.

This project would not have been possible without data provided by the Instituto Costarricense de Electricidad. I would specifically like to thank Ingeniero Rafael Chacón and Ingeniero Jorge Granados Calderón for assisting me in obtaining all of the information needed. Thank you especially to Ingeniero Granados Calderón for promptly responding to all of my emails and providing various data and answers to my questions. Mil gracias por toda su ayuda.

I would also like to thank Dalia Edelman, my Costa Rican liaison, and mother-in law, for helping me to translate many documents while in Costa Rica, and for helping me to obtain data while out of the country. Finally, I would like to thank my husband, David Laurencio, for driving me day after day to ICE and helping me to go through and translate documents, for feedback and editing assistance, for helping me with my Spanish, and for continually encouraging me. Without you, I could not have done this. Thank you.

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CHAPTER I

INTRODUCTION

Research Background

Dams have been built throughout the world for thousands of years, providing many benefits including recreational opportunities, flood control, stable water supplies, increased irrigation capabilities, and hydroelectric power. However, as the number of dams increased exponentially during the 20th century , so has the recognition of the negative impacts that these dams can have on the hydrology, geomorphology, and ecology of rivers (Brandt, 2000; e.g. Gregory and Park, 1974; Ligon et al., 1995; Williams and Wolman, 1984). Recently, as large inventories and databases have become available, research emphasis has shifted toward assessing large-scale impacts of dams and the spatial distribution of those impacts (e.g. Graf, 1999). These studies have resulted in full recognition of the large-scale dam impacts in temperate areas, especially in the United States (Graf, 1999; Graf, 2001), leading to an increasing emphasis on retiring and removing dams (Pohl, 2002). However, there has not been a parallel level of research in other areas, such as tropical regions of Central and South America. Dam construction is in fact on the rise in these regions (Brandt, 2000; Erskine, 1985). Because the tropics cover approximately one-third of the earth's land surface and contain 45% of the world's population, research on the effects of dams in these regions is especially important. Lack of scientific research on the impacts of dams in tropical areas

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This thesis follows the style and format of Journal of Hydrology is a critical problem because, until we fully understand these impacts, it will not be possible to determine ecologically sustainable options for water use and supply. It will also be difficult to determine the optimum dam management strategies for these countries.

The purpose of this research is to extend previous work on large-scale impacts of dams conducted in temperate areas to a tropical region. Costa Rica was selected as a representative case study in a tropical area because it has steady temperatures year-round and receives an average of about 250 centimeters of rainfall annually. Despite its small size (~51,000 km^2), Costa Rica produces 80 percent of its electricity from hydroelectric dams (Inman, 1998). The hydroelectric potential is much higher than the current output. As of 1999, the hydropower output was 5,085 GWh, only 12% of its technical potential, estimated to be 43,100 GWh/year, (World Energy Council, 2001). There are, therefore, plans to construct more hydroelectric dams in order to increase export of power to many central American countries (U.S. Department of State, 2003). The findings of this study are expected to enhance our understanding of hydrologic changes owning to dams in Costa Rica. Because Costa Rica is similar to many other tropical countries, results can also be extended to other areas. The results will also provide guidance for managing and planning for future dam construction in such areas, which is still occurring.

Objectives

The overall objective of this study is to understand the hydrologic impacts of dams in Costa Rica, a representative country in a tropical region. The central hypothesis is that dams in the tropics may not have as large an impact on surface hydrology as they do in temperate areas. This is because the increased precipitation available year-round results in a lower proportion of annual rainfall being stored in reservoirs. In turn, geomorphic channel adjustments following dam closure in the tropics are expected to be less dramatic than in temperate regions. Therefore, theory developed based on data from temperate areas may not apply to tropical regions.

The overall objective of this study will be accomplished by addressing three specific objectives. The first specific objective is to determine the quantity and geographic distribution of dams within Costa Rica, as well as their relation to land use and land cover. The working hypothesis is that there will be fewer dams currently in Costa Rica than in an equivalent area in the United States because dam construction has begun in the tropics only recently compared to temperate regions such as the United States (Brandt, 2000), where dam-building peaked approximately 40 years ago (Graf, 1999). Additionally, it is hypothesized that the majority of the dams will be found in the eastern half of the country because of higher precipitation in this area resulting from orographic affects (see figure on p. 18). Because the eastern half of the country has not only increased total precipitation but also a more steady year-round precipitation regime, the microclimate created on the eastern half seems more ideal for dam development. Furthermore, population is concentrated in one city (San Jose); within Costa Rica, it is therefore hypothesized that the majority of the area affected by dams will be dominated by forest and crops.

The second objective is to determine the effect of dams in Costa Rica on surface hydrology at a national scale, and assess the distribution of these impacts. The working hypothesis is that the proportion of available surface water trapped by reservoirs will represent a smaller impact in Costa Rica compared to the impact reservoirs have had in the United States (Graf, 1999). This is because higher precipitation in a tropical environment would be expected to diminish the impact of reservoir storage. In other words, because of high precipitation totals, the water stored behind a dam would be a lower proportion of the total annual precipitation compared to temperate areas. In Costa Rica, the impacts are also expected to be concentrated more on the Atlantic (eastern) side of the country, because of the higher precipitation regime present on the Atlantic side of the volcanic ridge (figures on p. 18 and p. 20).

The third specific objective is to analyze how individual dams may have changed downstream flow regimes. Dams are expected to decrease mean flow and peak flows and increase minimum flows downstream. This is the typical pattern observed in temperate regions (e.g. Chin and Bowman, 2005; Erskine, 1985). However, the working hypothesis for Costa Rica is that the flow regime changes will be smaller than in temperate regions. This is because the higher and steadier precipitation regime in Costa Rica would enable more frequent releases from reservoirs than in temperate environments, thereby maintaining a more natural flow regime downstream of dams in Costa Rica.

Organization of the Research

This thesis is organized into six chapters. Following the introductory chapter, Chapter II reviews the literature concerning the impacts of dams. This includes discussion of impacts on hydrology, geomorphology, and ecology, cumulative impacts, and an assessment of the state of knowledge of dam impacts on rivers in the tropics. Chapter III is an overview of the study area, including a brief description of the geology, climate classification, and precipitation patterns. The research methodology is outlined in Chapter IV. Chapter V presents the analysis results along with discussions and comparison of results with those from temperate regions. Final conclusions and future research needs are presented in the final chapter.

CHAPTER II

LITERATURE REVIEW

Introduction

Previous research on hydrologic and geomorphologic impacts of dams have focused on changes in flood magnitude and frequency (e.g. Chin and Bowman, 2005; e.g. Gregory and Park, 1974), changes in discharge (e.g. Erskine, 1985), changes in sediment transport (e.g. Grimshaw and Lewin, 1980), or changes in channel dimensions (e.g. Chin et al., 2002; e.g. Gregory and Park, 1974). Such evaluations of change have relied on an understanding of pre-dam conditions, and the majority of these studies have focused on a single dam and corresponding stream system. Although these types of studies have continued, a new trend of studying large-scale effects of several dams on a larger regional scale has also emerged (e.g. Dynesius and Nilsson, 1994; Graf, 1999; Rosenberg et al., 2000). Larger-scale studies have increased as large inventories and databases have become more accessible in recent years.

The following paragraphs summarize the effects of dams. After a brief discussion of establishing pre-dam conditions, three orders of impacts, as described by Petts (1980) are examined. This is followed by a description of recent regional assessments of large-scale impacts, and then a summary of current knowledge of dam effects on rivers in tropical regions.

Determining Pre-Dam Conditions

Ideally, a thorough study of the potential effects of a dam should be done prior to, throughout the building of, and after completion of the dam to document changes that a river system undergoes (e.g. Hadley and Emmett, 1998). Unfortunately, this seldom occurs because of a lack of pre-dam data. Many of the studies on dam impacts investigate the system only after the dam has been in place for some time. To accommodate for the lack of historical knowledge, a space-time substitution approach, first suggested by Wolman (1967), is commonly used. This method approximates pre-dam characteristics by using similar neighboring streams not impacted by the disturbance to gain some knowledge of the expected hydraulic characteristics downstream of the dam in the absence of a dam. This method has been expanded to include comparison of upstream characteristics versus those downstream of the dam (e.g. Chin et al., 2002). With the space-time substitution method, knowledge of the prior characteristics of a stream can be approximated in the absence of historical knowledge, and it is possible to estimate what changes may have occurred because of the dam. In the tropics where data are lacking, the space-time substitution may be a viable option for dam studies.

First Order Impacts

First order impacts involve process alteration, specifically alteration of the flow regime and sediment yield below the dam (Petts, 1980). Downstream of an impoundment, changes in flow regime can be reflected in a decrease in flood magnitude and frequency and a decrease in mean discharge or peak flow. For example, Gregory and Park (1974) compared peak discharges immediately downstream of Clatworthy reservoir in Somerset, England with an adjacent, comparable catchment, and found that peak discharges immediately downstream from the reservoir were typically one-third to one-half the magnitude of the adjacent channel. Similarly, Erskine (1985) reported a reduction in mean annual runoff of about 2,100,000 cubic meters after the closure of the Glenbawm Dam in Australia. Additionally, because large dams are often built for flood control, they can have the effect of completely eliminating large floods (greater than 5,000 cfs). This was the case for Yegua Creek, Texas, where peak discharges were decreased by approximately 85 percent after the closure of Somerville Dam (Chin and Bowman, 2004). The extent of the decrease in discharge, flood magnitude, and flood frequency depends on the size and type of dam and whether floodwaters are impounded or released in surges (Gregory and Park, 1974). However, although magnitude commonly decreases in the impounded stream, minimum flows are often increased. For example, in Yegua Creek, mean minimum monthly flows downstream of Somerville Dam increased from 12 cfs to 58 cfs following dam closure (Chin and Bowman, 2005). Additionally, discharges often increase in other streams surrounding a dammed river because of redirection of the water from the dammed stream to other watersheds (Brandt, 2000). Therefore, studying only single watersheds, when considering the impacts of a dam, may not produce a full understanding of changes that are occurring.

Sediment-related changes downstream of dams often involve a decrease in sediment load. The change typically results from sediment being trapped by the impoundment. For example, Grimshaw and Lewin (1980) found during a two-year study that suspended sediment yields on the impounded Rheidol, in Britain were 7 and 16 times less than those found on the Ystwyth, a comparable, naturally flowing river. These differences were attributed to trapping of sediments by the impoundment, as well as a decrease in bank erosion and lower carrying capacity of the stream. Andrews (1986) reported that, although mean annual discharge has not changed downstream of the flaming Gorge Reservoir in Utah, peak discharges capable of entraining bed sediments have decreased significantly. Additionally, only 20% of the contributing sediments originate upstream of the reservoir, and therefore have the potential to be trapped by the impoundment. This has resulted in a 54% decrease in suspended sediments 105 river miles downstream from the reservoir. The distance downstream that the decrease in sediment yield persists depends on many factors, including degree of erosion immediately downstream of the dam, number of tributaries contributing sediments, size of peak flows, and dam operation.

Second Order Impacts

Second order impacts are the changes in channel morphology and in invertebrate populations as a result of changes in flow and sediment transport regimes (Petts, 1980). Changes in morphology are reflected primarily in width, depth, and channel capacity measurements. After a change in water flow, channel width is the initial primary adjustment, followed by other variables (Leopold and Wolman, 1957). However, channel capacity has been found to be a more accurate measure of change in channel morphology (Gregory and Park, 1974). Channel capacity is a measure of the amount of discharge (volume of water per unit time) a stream channel can carry without flooding, and is measured by the cross-sectional area of the stream channel. Gregory and Park (1974) found that channel capacity immediately downstream from the Clatworthy reservoir, in Somerset England was only 54% of the original channel capacity and that this decrease in capacity persisted for at least 11 kilometers, until the catchment area for the river increased to a size four times that of the area draining into the reservoir itself. For Yegua Creek downstream of Somerville Dam in Texas, channel size was 35% of what was predicted for a comparable channel not affected by the dam (Chin et al., 2002). This change was primarily a function of a decrease in channel depth. The reductions were less dramatic farther downstream, where unregulated tributaries provided a greater amount of water and sediments (Petts, 1979).

Impounded rivers typically result in a decrease in the number of macroinvertebrate species in conjunction with an increase in the density and biomass of the species that are present (Commission on Geosciences Environment and Resources, 1991). For example, a long-term study of the macroinvertebrates of the Green River found that prior to construction of the Flaming Gorge Dam in 1963 the invertebrate fauna were primarily insects with a density of ~1000 insects/m^2. Following dam closure, insect diversity downstream of the dam decreased from 30 species to only 1. Additionally, immediately after dam construction invertebrate mean densities increased to 4280 insects/ m^2, and between 1993 and 1999, the mean density had increased to between 8100 and 11800 insects/m^2 (Vinson, 2001).

One study in Puerto Rico, a tropical environment, found that even low-head dams can have severe effects on aquatic macroinvertebrate populations (Benstead et al., 1999). This study examined shrimp larvae migration upstream. It was found that the shrimp larvae suffered a mean mortality of 42%. Further analyses of longterm mortality revealed a possible mortality rate as high as 62% when considering the mean abstraction rate of water by the dam. The larval mortality rate was found to be dependent on the discharge rate, with higher discharges (and lower abstraction rates) decreasing larval mortality.

Third Order Impacts

Changes in channel hydrology and morphology, as well as invertebrate community composition, can have severe effects on the ecology of a stream, considered third order impacts (Petts, 1980). For example, one of the few tropical studies found that the building of the Petit-Saut dam on the River Sinnamary in French Guiana, South America, led to a shift in the dominant fish species downstream of the dam (Ponton et al., 2000). Prior to dam closure, the Characiformes taxon represented >60% of the fish taxa in the stream. However, this number decreased to 50% of the species upon dam closure. A more dramatic change was revealed when considering the proportion of individuals. Prior to dam closure, Characiformes juveniles represented >80% of the individuals. This number decreased to 20-30% upon dam closure (Ponton et al., 2000). These changes were attributed primarily to the decrease in flow downstream of the dam. This prevented the surrounding floodplain from being inundated as it normally would be during the rainy season.

Elsewhere in the McKenzie River in Oregon, the damming of two tributaries has led to a decrease in mid-channel bars and islands, which has resulted in a decrease in braiding and the development of a single-thread channel (Ligon et al., 1995). The reduction of bars and islands and the decrease in coarse sediments in the channel have limited spawning habitat availability. This has led to a change in the population dynamics, with a reduction in population size of 50% since the closure of the second dam in 1969. Although the dramatic decline in population size cannot be attributed entirely to decrease in spawning habitat, it is a significant factor. Changes in microhabitat of fish also results directly from changes in discharge. In the Deerfield River in Connecticut, daily fluctuations in discharge, resulting from water releases from a hydroelectric plant, have led to a more homogenous habitat downstream (Bain et al., 1988). In a similar, naturally occurring stream >90% of the fish individuals are small, and utilize shallow, slow moving areas of the stream. This microhabitat fluctuates so greatly during the day that it is essentially eliminated in the Deerfield River. While those species have been negatively impacted, more generalist species, and larger fish that use deeper more fast-moving waters have increased in density.

While fish community changes seem the most obvious result of river channel modification, other taxa, particularly riparian vegetation (e.g. Jennings, 1999), have been well documented. Additional studies have investigated impacts on other taxon including mammals, birds, and amphibians (e.g. Nilsson and Dynesius, 1994; Reese and Welsh Jr., 1998). Because the changes in discharge and geomorphology result in a change of habitat within the stream as well as along the riparian corridor, changes which will occur to a specific area are difficult to predict, especially in tropical areas where baseline data are lacking.

Large-Scale Effects

Improved understanding of the impacts of individual dams has provided a strong foundation for investigating the effects of multiple dams on a larger scale. Graf (1999) assessed the cumulative hydrologic effects of dams in the United States using "potential reservoir storage" as a representation of the hydrologic impact. Potential reservoir storage is the volume of water that the reservoir is capable of holding. Graf (1999) reported that only 3% of the dams in the United States are considered large dams (reservoir storage greater than $1.2 \times 10^9\,m^3$), yet they impound 63% of the total storage for the country. Because of this, Graf (1999) concluded that the smaller dams may impact rivers insignificantly at a national scale, although the effects of these dams at regional scales could be important.

Hydrologic impacts of dams in the United States are highly spatially variable (Graf, 1999). Analyzing the ratio of potential reservoir storage of dams to their drainage areas, which illustrates the magnitude of potential change in river flows, Graf (1999) found that the highest ratio in the United States is in the South Atlantic-Gulf Region, where dams could store 345,000 m^3 of water per square km of drainage area. This implies that the dams have great potential impacts on streamflow volume in the South

Atlantic-Gulf area, which could have severe water resource and ecological repercussions in that region. Another significant measure of large-scale hydrologic effects of dams is a comparison of potential reservoir storage to mean annual runoff. If reservoirs capture a significant amount of the annual runoff this makes water unavailable for other purposes (e.g. ecological and societal needs). While overall, the annual runoff in the United States is slightly greater than the total storage, reservoirs in some areas, specifically Rio Grande and Upper Colorado basins, impound more than the annual runoff (Graf, 1999). These variations suggest regional trends not apparent at the national scales. Regional assessments, therefore allow a more detailed understanding of the trends in distribution of dams as well as the hydrologic impacts that are occurring across regions.

At an even larger scale, Dynesius and Nilsson (1994) analyzed dam impacts in the northern third of the world (North America north of Mexico, Europe, and the republics of the former Soviet Union). They quantified the impact of reservoirs as the percentage of mean annual discharge that can be contained in the reservoir, similar to Graf's (1999) ratio of reservoir storage to mean annual runoff. The highest storage value reported in this study was for La Grande Riviere in Quebec, where reservoirs store 96% of the river basins' mean annual discharge (Dynesius and Nilsson, 1994). Overall, 42% of the river systems analyzed in the northern third of the world were strongly affected by flow regulation (Dynesius and Nilsson, 1994). This is based on analysis of both main channels and tributaries, with the category of "strongly affected" meaning that less than ¼ of the main channel length remains dam-free (Dynesius and Nilsson, 1994). When analyzing rivers by their biomes, 20% of the river systems that flow primarily through subtropical and temperate rain forests were found to be strongly affected by fragmentation and flow regulation (Dynesius and Nilsson, 1994).

Impacts of Dams on Rivers in Tropical Areas

Despite the fact that tropics cover a significant portion of the earth's surface, studies of dam impacts on rivers in the tropics are noticeably lacking. Lack of research in the tropics may be attributed to recent dam development, resulting in limited data and comparatively few dams (Pringle et al., 2000). Studies of downstream effects of dams conducted in the tropics have focused on biotic impacts (e.g. Benstead et al., 1999; Ponton et al., 2000). However, the majority of studies are limited by the lack of pre-dam information. In fact, some ecologists have equated the knowledge of fish in the Neotropics to the early 19th century in North America (Winemiller, 1996). As a result, many of these studies are theoretically based (based on knowledge of temperate regions), rather than descriptive and predictive based on an understanding of the tropical region.

Literature on hydrologic or geomorphic adjustments downstream of dams in tropical areas following dam closure is non-existent. Whereas in temperate studies, results have shown changes in peak flows, mean discharge, and minimum flows, comparable research has not been conducted in tropical regions to determine if flow regime alterations may be similar in those areas, although La Rovere and Mendes (2000) have described elimination of seasonal flooding of river banks downstream of dams. The lack of knowledge of the impacts of dams in tropical regions prohibits optimum dam planning and management that will minimize downstream modification. The paucity of research also hinders theory building regarding channel adjustments to river regulation. Fundamental studies are needed to begin to outline the hydrologic impacts of dams in tropical regions to fill the gap in the current state of knowledge.

This research extends the large-scale analysis of dam impacts, along the lines of Graf and others, to Costa Rica, as a first step to expanding our knowledge of dam impacts in tropical regions. Such an analysis will provide baseline data for theory building. Because the ecology and biodiversity of Costa Rica are vitally important to the country's economy, and large hydroelectric dams can have significant effects on riverine habitat and ecology, this study promises to shed light on best management strategies for the country as it plans to build more hydroelectric dams.

CHAPTER III

STUDY AREA

Costa Rica is located at approximately 10˚ 00’ N latitude and 84˚ 00’ W longitude and is part of the isthmus connecting North and South America (Figure 1). Despite its small size, about 51,100 square kilometers, Costa Rica contains roughly 5 percent of the world’s biodiversity (Inman, 1998). It is home to approximately 850 bird species, over 400 amphibian and reptile species, 8,000 higher plant species, and approximately 10 percent of the known butterfly fauna in the world (Janzen, 1983; Knox and Marston, 2003; Savage, 2002). In 1970, the Servicio de Parques Nacionales de Costa Rica (SPN), or the National Park Service, was established as part of the Ministerio de Agricultura y Ganadería, with the intention of preserving the natural areas and biodiversity of Costa Rica (Janzen, 1983). Currently, 30% of Costa Rica is protected in biosphere and wildlife preserves (Knox and Marston, 2003). Since the establishment of the SPN, ecotourism has grown dramatically, and by 1995 it was generating US $659.6 million per year. Ecotourism surpasses both coffee and bananas as the largest generator of foreign revenues (Instituto Costarricense de Turismo, 1995).

The geology of Costa Rica ranges in age from the Jurassic to Quaternary periods. The rocks are mainly sedimentary or volcanic (Janzen, 1983). Between 3 and 40 million years ago, Costa Rica and the rest of the isthmus connecting North and South America was an archipelago of volcanic islands being formed as the Caribbean Plate subducted the Cocos Plate. The convergence of the two plates created the volcanic

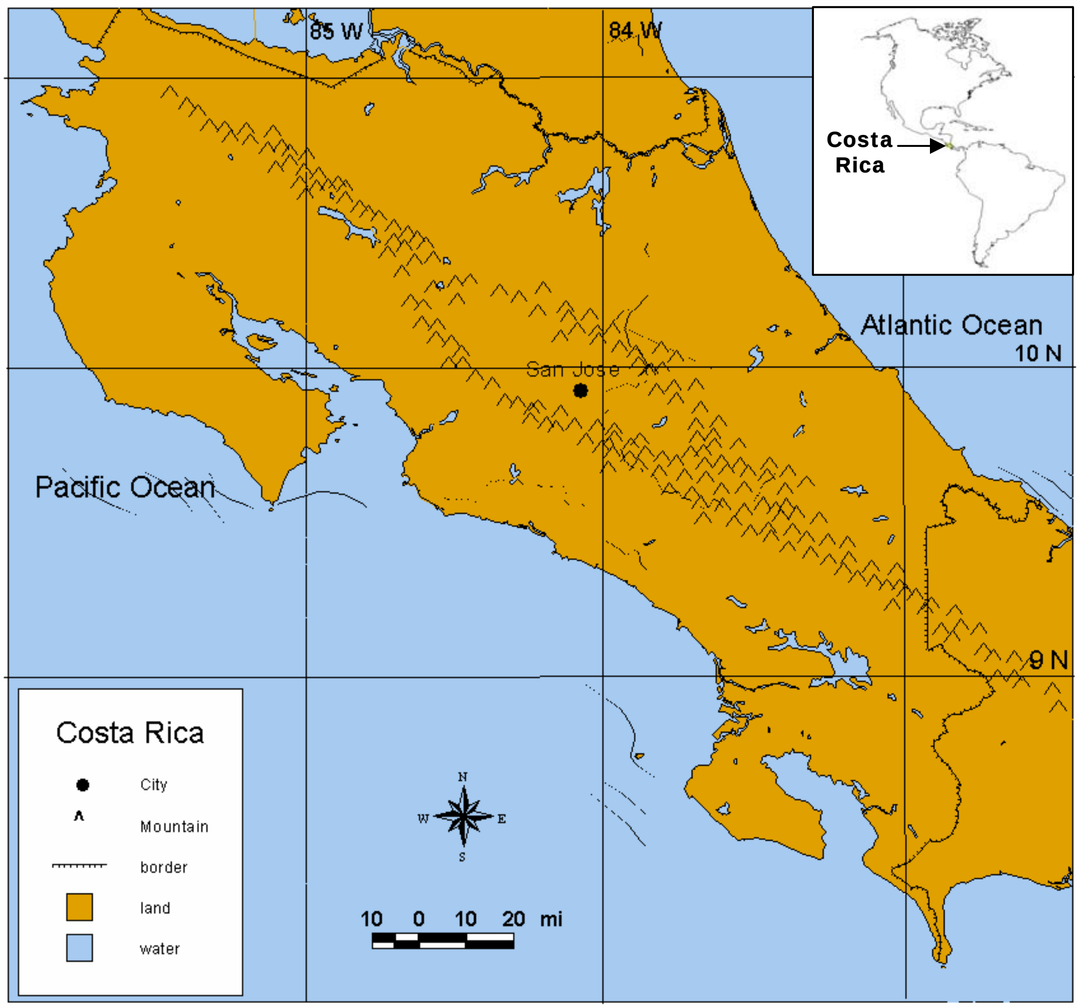

Fig. 1. Map of Costa Rica. Costa Rica is located in Central America on the isthmus connecting North and South America. Note that wind direction is from east to west.

mountain ridge of Costa Rica that runs northwest to southeast (figure 1). This ridge controls the hydroclimatology of the country to a large extent because of orographic effects.

Because of its proximity to the equator, Costa Rica's climate is affected by both the northeasterly trade winds that are part of the Intertropical Convergence Zone and an even amount of solar radiation throughout the year. Together, these factors produce steady temperatures year-round, with the average temperature of the warmest month not exceeding the average temperature of the coolest month by more than 5˚ C in any given area (Janzen, 1983). The Pacific Coast, however, does receive a higher monthly maximum temperature than does the Atlantic Coast for the same elevation (Janzen, 1983). Because of steady temperatures year-round and ubiquitous amounts of rainfall, Costa Rica has a tropical climate (Christopherson, 2003).

The northeasterly trade winds combined with Costa Rica's mountainous topography result in unique precipitation patterns for the Atlantic and Pacific sides of the country. The Atlantic side of the country is the windward side, and it therefore receives a greater amount of precipitation. The western, Pacific side is drier because it is in the rainshadow of the volcanic ridge that divides the country (figure 2). However, rains typically occur earlier in the day on the Pacific side than on the Atlantic side (Janzen, 1983). The rainy season in Costa Rica also begins earlier on the Atlantic coast, in April, and ends later, in January, in contrast with the Pacific coast, where it begins toward the end of May and ends in November (Janzen, 1983).

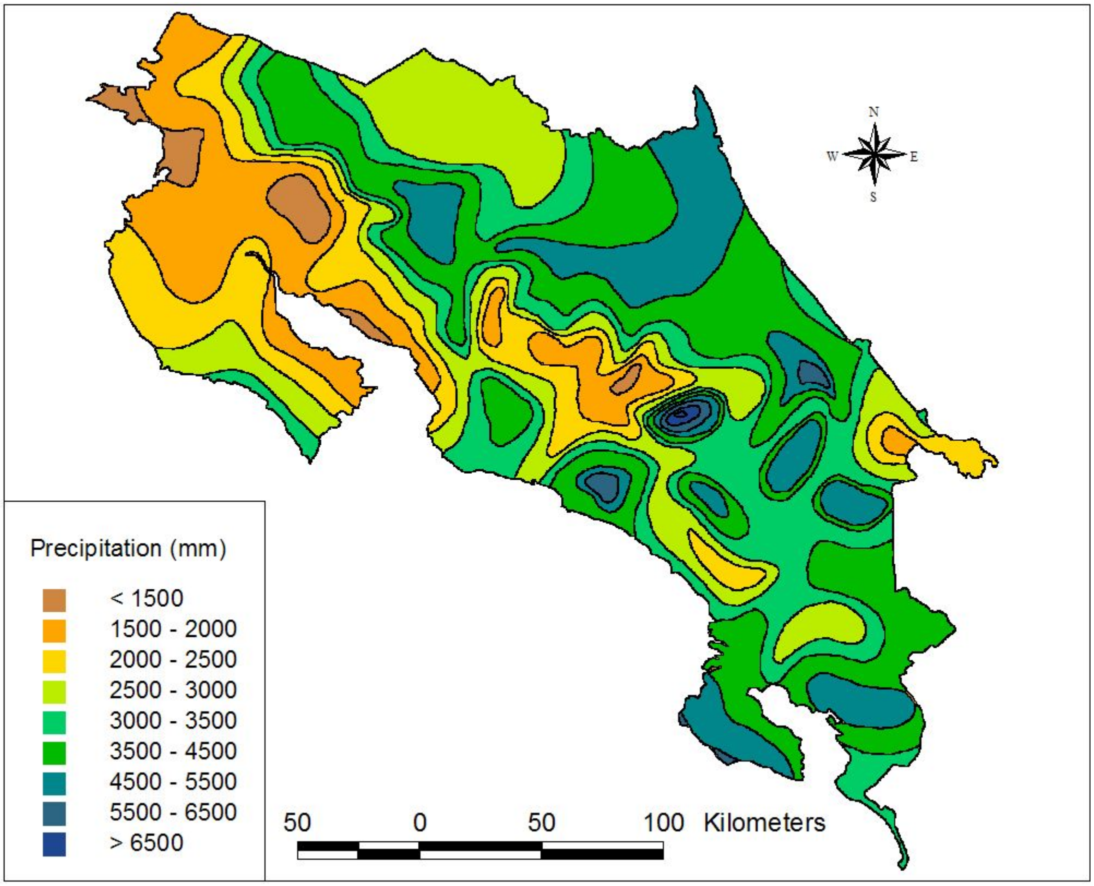

Fig. 2. Mean annual precipitation in Costa Rica. Taken from the Climatological Atlas of Costa Rica (Barrantes F. et al., 1985).

CHAPTER IV

METHODS

Different methods were employed to address the three specific research objectives including analysis in a geographical information system, as well as, graphical and statistical analyses. The following pages include a description of all data sources utilized in the various analyses along with a discussion of the data preparation. Finally, the methods used to address each specific objective are outlined.

Data Sources

In order to accomplish the three stated objectives, the following data were needed:

- Number, location, and characteristics of dams in Costa Rica
- Discharge data downstream of representative dams
- Digital elevation model to provide topographic information and derivation of stream networks used to georeference dam information
- Land use information for drainage basins containing hydroelectric dams
- Annual precipitation for basins containing dams and for the entire country

Dam and flow data were obtained from Instituto Costarricense de Electricidad (ICE), the organization that operates the hydroelectric dams in Costa Rica. Daily discharge data were available in table format for gauging stations operated by ICE. Data were available for some hydrologic stations as early as 1955. Other data, including reservoir capacity, drainage basin area, and dam location, were extracted from documents obtained from ICE archives.

Digital elevation models (DEMs) are the most detailed representation of surface topography available in digital form. DEMs are grids with each cell representing the ground surface elevation of the corresponding parcel of land. For this study, a 90-meter (3 arc-second) resolution DEM was used to derive drainage basins and the stream network for Costa Rica for all analytic components. The DEM was created from elevation data obtained by the Shuttle Radar Topography Mission (SRTM) in February of 2000 (National Aeronautics and Space Administration et al., 2002). Because satellite data was used, the accuracy of the data is limited. Elevation values derived from the SRTM are not always at ground level. For example, in forested regions, the elevation values are actually the canopy elevation, rather than the ground. However, data derived from satellite are the best source for a tropical environment because the radar is able to penetrate through cloud cover, and therefore, results in a DEM without data gaps that are commonly caused by cloud cover. Therefore, the SRTM data was deemed the best source for this project.

The *Digital Chart of the World*, a spatial database providing political boundaries, elevation, hydrography, physiography, population, and vegetation (National Imagery and Mapping Agency, 1997) was purchased to verify elevation data and river locations for Costa Rica derived from the digital elevation model. The primary source for the database is the 1:1,000,000-scale Operation Navigation Chart (ONC) series co-produced by the military mapping authorities of Australia, Canada, United Kingdom, and the United States. The land cover layers were also used in the analyses.

The Instituto Meteorologico Nacional (National Meteorological Institute) (IMN) of Costa Rica published a Climatological Atlas containing isohyetal maps of precipitation (annual and monthly) for the entire country. The maps are based on precipitation stations maintained by the IMN throughout the country. Data from 1961-1980 were used to calculate averages for the isohyetal maps. For this analysis, the annual precipitation map was used.

GIS Data Preparation

The general approach to this research was to use a geographic information system (GIS) to analyze the location and distribution of dams and their impacts. A database of dams in Costa Rica, georeferenced to a map projection, provides a visual representation of the spatial distribution of dam, and enables analysis of land use within drainage basins containing dams. In addition, a GIS approach will assist future analyses including hydrologic modeling to predict impacts of further dam development in Costa Rica. The following paragraphs detail the specific procedures used to prepare the data for analysis.

The first step in processing the GIS layers was to georeference all data layers to a common datum and projection to enable spatial overlap. The map projection selected for this process was the Lambert Conformal Conic projection, which is also used by

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INPUT
PROJECTION GEOGRAPHIC
UNITS DD
PARAMETERS
OUTPUT
PROJECTION LAMBERT
UNITS METERS
PARAMETERS
09 56 00
11 00 00
-84 20 00
10 28 00
500000
```

Fig. 3. Sample projection file. Parameters used to georeference shapefiles from the National Imagery and Mapping Agency to Lambert Conformal Conic Projection.

agencies in Costa Rica for their GIS layers (e.g. Costa Rica Ministry of Agriculture and Livestock, 2001). Figure 3 shows an example of one of the projection files. The parameters used for all output projections include two standard parallels (9˚ 56' 00" and 11˚ 00'00"), a central meridian (-84˚20'00"), a latitude of origin (10˚28'00"), false easting (500,000 meters), and false northing (271,820.522 meters). The projection transformations were done in ArcInfo 8.2 (2002), a GIS commonly used for geoprocessing and data analysis.

Next, there were locations for which no elevation values were available. These "no data" gaps needed to be filled with interpolated values. This was achieved using the nearest neighbor re-sampling method. This method fills any missing cell values with the value of the nearest cell. Upon elimination of all "no data" gaps, the DEM was analyzed to correct any inaccurate elevation values in order to eliminate sinks. A sink is a cell or group of cells surrounded by other cells with higher elevation values. When running a hydrologic model, the water would flow to the sink and have nowhere to go. While there are naturally occurring sinks, such as reservoirs or lakes, many sinks in the DEM result from erroneous elevation values (Chang, 2002). Leaving sinks in the DEM would result in an erroneous hydrologic network. To eliminate sinks, the georeferenced DEM of Costa Rica resulting from the merge process (eliminating "no data" gaps) was filled using the 'fill' command in ArcInfo (2002). There were 213,296 sinks that were filled during this process.

One last step was required to prepare the DEM to derive the drainage network and drainage basins. The DEM acquired from the SRTM data, covers areas that are not a part of Costa Rica, including oceans to the east and west. Therefore, the DEM must be clipped so that it only contains the elevation values for the land. This was achieved using the ‘selectmask’ command in ArcInfo (2002). Included in the NIMA *Digital Chart of the World* is a layer including the political boundaries of Costa Rica (National Imagery and Mapping Agency, 1997). This layer is converted to a grid, which assigns ‘no data’ values to all ocean areas, and a single value to the land areas. This new grid is considered the mask. The ‘selectmask’ command converts all cells in our input DEM, which have been assigned ‘no data’ values in our mask, to ‘no data’ values. The resulting DEM contains ‘no data’ values for all ocean areas (figure 4), and is now ready to derive the drainage network and other hydrologic inputs necessary for the hydrologic modeling.

In order to derive the drainage network, flow direction must first be determined. This is achieved using ArcInfo (2002), which determines the direction of flow over the land using an eight-point pour algorithm. A basic assumption of this method is that flow only occurs in one direction. The direction of water flow is dependent on the steepest gradient between a cell and its eight neighbors (Chang, 2002). Gradient is calculated as the change in elevation divided by the distance between the centers of the two cells. For example, for a cell size of 1, the distance between orthogonal cells is 1 and the distance between the diagonal cells is 1.41 (the square root of 2). An example of a flow direction determination for a grid with a cell size of 1 is given in figure 5. This is an important step in the DEM preprocessing because several of the subsequent analyses

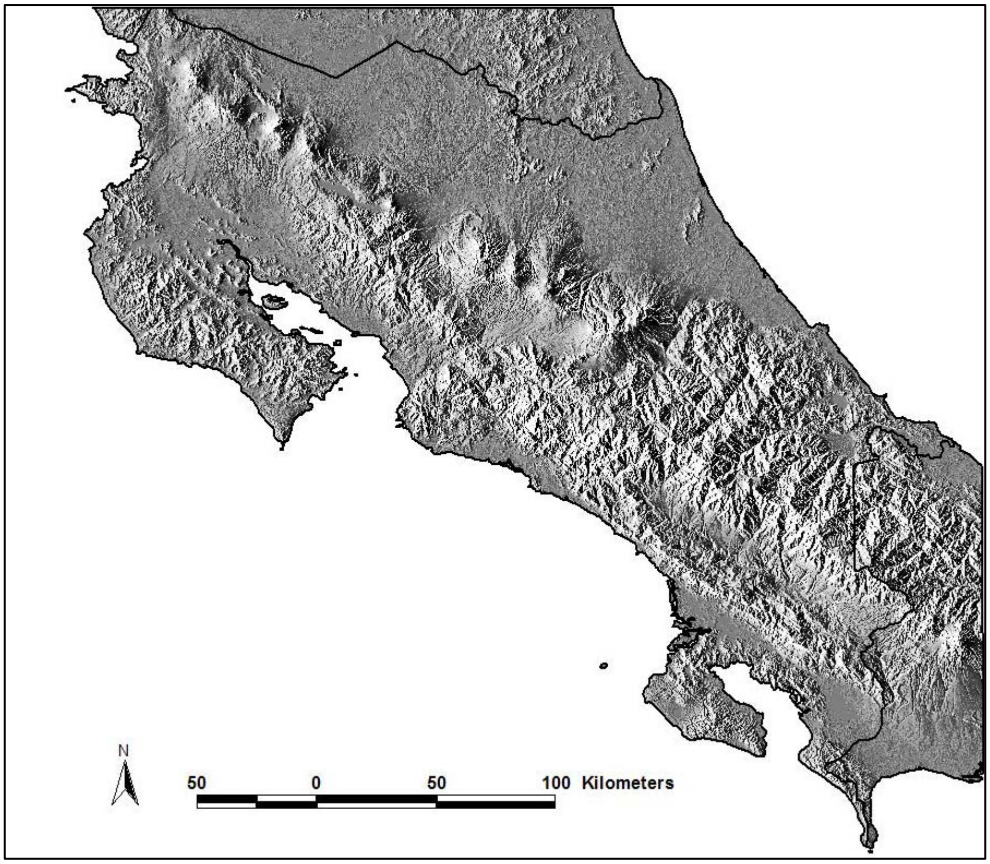


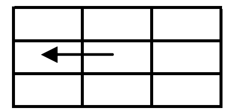
Fig. 4. Digital elevation model.

24	20	30
19	23	26
31	25	22

(a)

-0.7	+3.0	-5.0
+4.0		-3.0
-5.7	-2.0	0.7

(b)



(c)

Fig. 5. Example of flow direction determination. (a) Elevation values for a 3x3 grid. (b) Calculated gradient values for the center cell and its surrounding 8 cells. (c) Direction of flow toward the largest gradient.

depend on the derivation of this grid. The flow direction grid for Costa Rica is show in figure 6.

The flow accumulation grid is the next step in the terrain preprocessing. This step produces a new grid based on the flow direction grid previously derived. The flow accumulation grid determines the number of cells that flow into each cell. For example, streams will generally have a high accumulation value, whereas ridges will have values of zero (Chang, 2002). The drainage network is then derived from this flow accumulation grid (figure 7). Once the flow direction and flow accumulation grids have been derived, the stream network for Costa Rica can then be derived. This is the final step in data preparation.

Stream definition is dependent on a threshold value. Smaller threshold values result in more subbasins. Using ArcInfo (2002), a grid of streams was created using a threshold value of 1000. This means that all cells that had a flow accumulation of 1000 cells or greater was considered to be a part of a stream. The stream network and the flow direction grid are then used to create a grid containing the Strahler (1952) stream order of each stream segment. The Strahler system assigns a value of 1 to each exterior stream. The order then increases when two stream segments of the same order come together. Using the stream order grid and the flow direction grid, a vector coverage of the stream network of Costa Rica was created (figure 8). This layer is important because it is a georeferenced drainage network that can be used to georeference and map the hydroelectric dams in Costa Rica and create a spatial database.

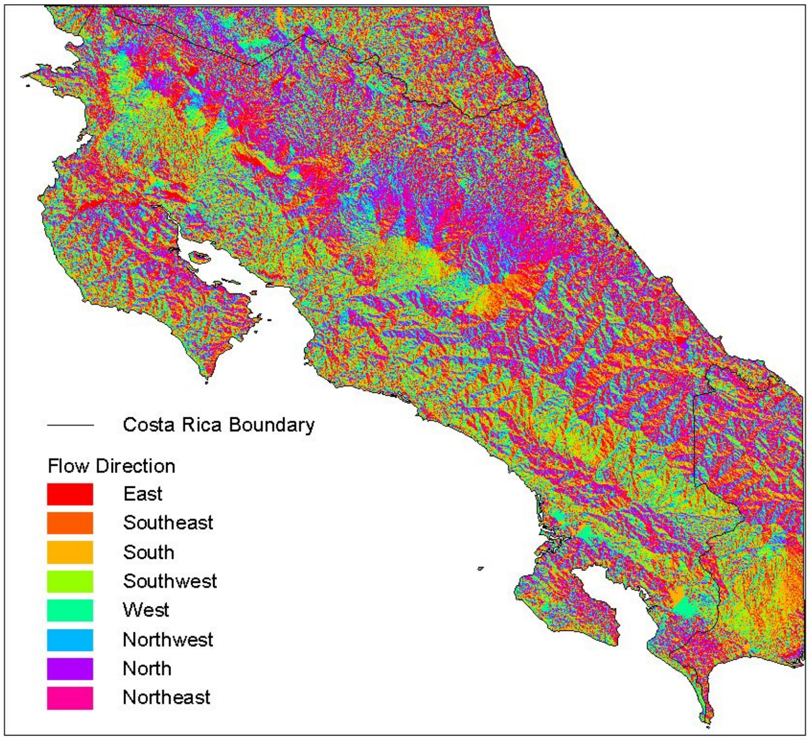


Fig. 6. Flow direction grid for Costa Rica.

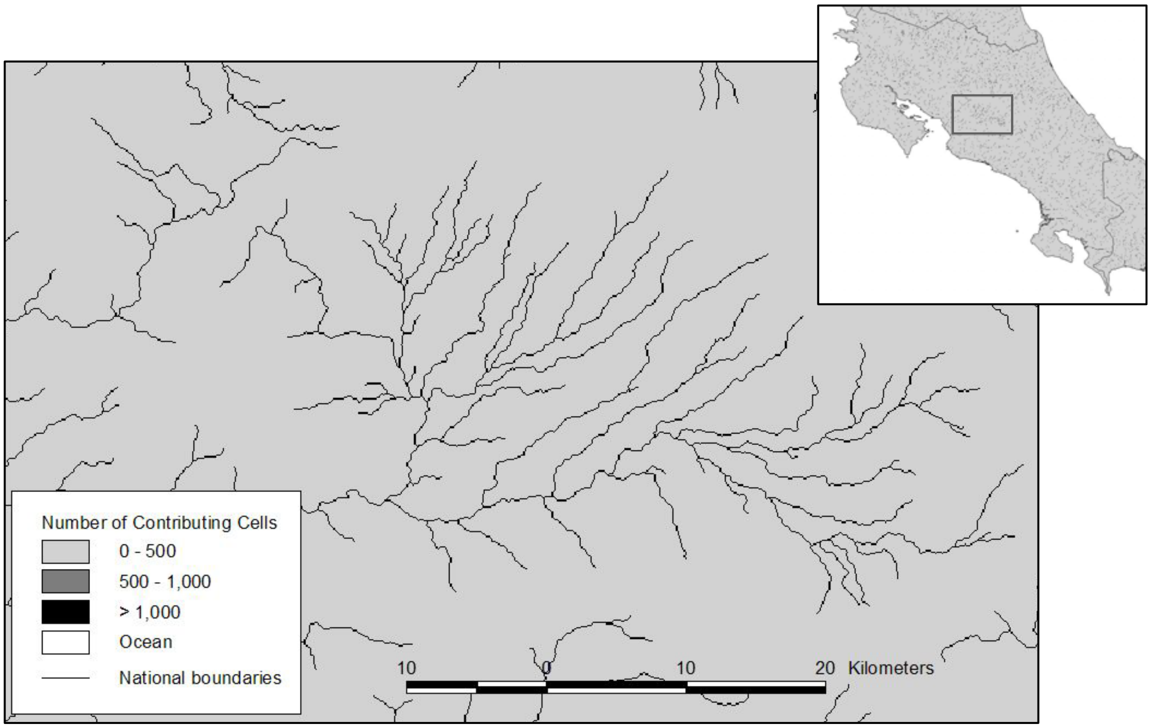


Fig. 7. Flow accumulation grid for Costa Rica.

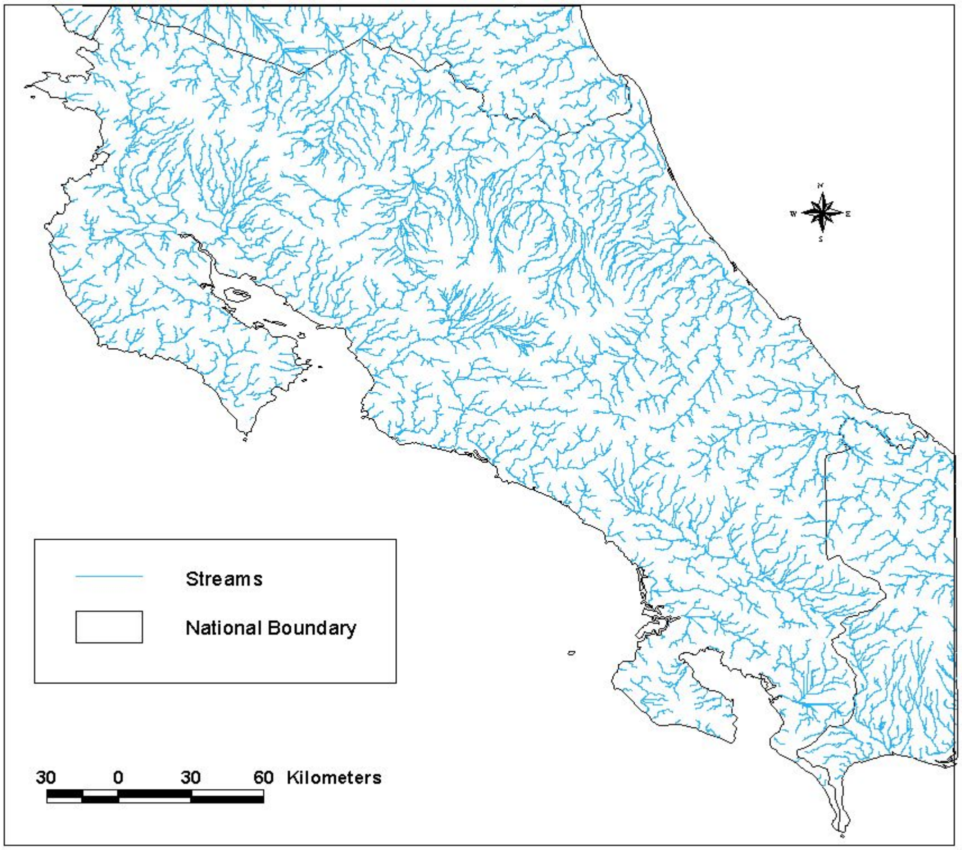


Fig. 8. Vectorized stream network.

Data Analysis: Geographic Distribution of Large Dams in Costa Rica

To address the first research objective maps obtained from ICE were georeferenced and analyzed in a geographic information system (Bel Ingenieria S.A. and Bookman-Edmonston Engineering Inc., 1978; Centro Cientifico Tropical, 1987; Freer Hernandez, 1979; Instituto Costarricense de Electricidad, 1964; Instituto Costarricense de Electricidad, 1985; Sector de Energia (I.C.E.), 1993). This involved scanning in each map separately from various documents and saving it as a tiff image. Next, the individual tiff images were georeferenced by adding each image to ArcMap 8.2 (2002) as a data layer along with a map created in ArcView containing the drainage network coverage of Costa Rica. Using the georeferencing extension in ArcMap, identical points were found on the maps and the georeferenced drainage network. Once at least four tic marks were found, and the scanned image is lined up with the drainage network, the map was rectified and a new georeferenced map grid created. Once the tiff images are georeferenced, coordinates for the dams were ascertained and entered into a database via Microsoft Excel (2003). Data for reservoir capacity, dam height, and dam width at crest were also entered into this database. The map of the dams was overlaid onto the digital elevation model, thus revealing the geographic distribution of the dams. Additionally, this map was queried to determine the elevation of all of the dams to examine the vertical distribution of the dams. Lastly, the dam locations were used to derive drainage basins for analysis of land use and hydrologic impact (objective two).

Drainage basins were defined for each dam using ArcInfo 8.2 (2002) (figure 9). To achieve this, the point coverage of the dams was used to create a grid with the

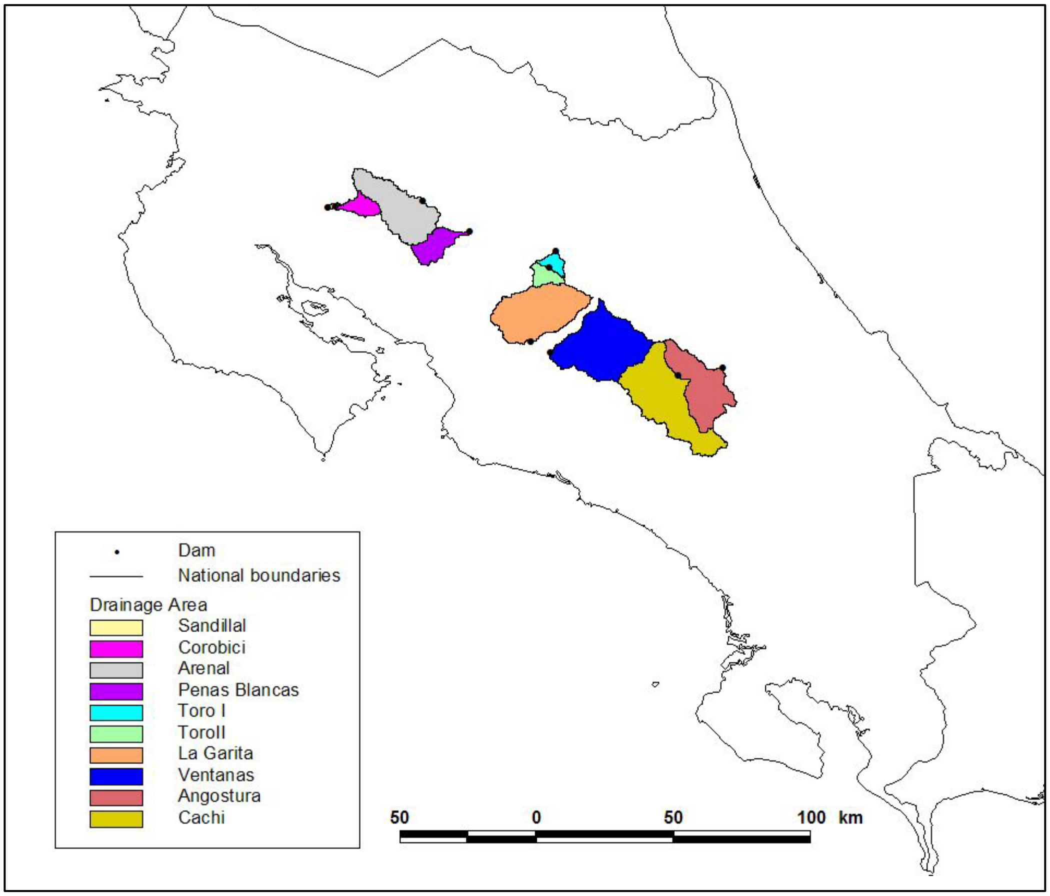


Fig. 9. Drainage basins corresponding to the large dams in Costa Rica.

corresponding points (using the ‘selectpoint’ command and the DEM). These points were considered outlet points and the corresponding watersheds were created using the ‘watershed’ command in ArcInfo, which utilizes the flow direction grid to determine the watersheds. Before analysis could procede, the watersheds were converted to polygons using the ArcView extension HEC-GeoHMS, which was created to prepare data to be analyzed in HEC-HMS (Hydrologic Engineering Center, 2003). Although HEC-HMS was not used to model flow, the extension allowed creation of the drainage basin coverage which was georeferenced and used for impact analyses including land cover.

GIS layers of land cover obtained from the *Digital Chart of the World* (National Imagery and Mapping Agency, 1997) were overlaid with the drainage basin maps. The percentage of various land cover types (sand, trees, grass, crops, or city) within the drainage basin area for each dam was calculated. Any relations of dam distribution to land cover were thus revealed. The land cover maps used in this publication were from 1993, therefore show only a snapshot in time, and are expected to have changed over the past 10 years.

Data Analysis: How Dams in Costa Rica Affect Surface Hydrology

To address the second research objective, this study adopted the criterion used by Graf (1999), which describes the large-scale hydrologic impact as being equal to the potential reservoir storage created by the dams. The potential reservoir storage is the volume the water held by the reservoir. There are two classifications of reservoir volume: active reservoir storage and gross reservoir storage. Active reservoir storage describes the volume of water that can be stored and subsequently released from the dam. Gross reservoir storage includes the bottom water that is below any outlet, and therefore cannot be used or released (Dynesius and Nilsson, 1994). Potential reservoir storage of dams is a relative measure of the likely changes in flow regime of streams affected by those dams. For this analysis, the active reservoir storage is used because it is this storage that is changing and impacting surface hydrology. To indicate the potential cumulative impact of reservoir storage, the active reservoir storage of all large dams was summed. This value is compared to the total annual precipitation of Costa Rica.

To calculate the annual precipitation, the isohyetal map from the Climatic Atlas of Costa Rica (Barrantes F. et al., 1985) was scanned to create a tiff image and was georeferenced in the same way the dam maps were georeferenced in ArcMap (2002). The map was then added to ArcView (2002) and a line shapefile was created. The isohyetal contours were used to create a precipitation grid in ArcInfo using the "topogrid" command, with a grid cell size of 1 km. Next, bilinear resampling in ArcInfo was used to create a final precipitation grid with a cell size of 90 m. The final 90 m grid was added to ArcView along with the shapefile containing the drainage basins. The precipitation within each drainage basin was then calculated based on the precipitation grid.

Ideally total annual runoff would be used to keep results comparable to those reported by both Graf (1999) and Dynesius and Nilsson (1994). However, total annual runoff for the country and for many of the basins was not available. Attempts were made to estimate predicted annual runoff based on known runoff values. This, however, could not be accomplished. The percentage of annual precipitation that results in annual runoff ranged from 37% to 89% depending on the basin. However, the 63% loss is assumed to be an outlier. Still, not enough data were available to arrive at an accurate estimation of annual runoff. Therefore, comparison of total reservoir storage to total average annual precipitation provides a rough estimate of the potential cumulative effect of dams on the hydrology of Costa Rica. Although, obviously this is a crude measure and if runoff data were available, that would provide a much better estimate of the potential impact of reservoir storage.

Subsequent to the national comparison, the distribution of the potential impacts (by basin) was determined. To determine the distribution of impacts, the ratio of reservoir storage to total average annual precipitation was calculated for each basin containing a large dam. Additionally, the ratio of reservoir capacity to drainage basin area was determined. This illustrates the distribution and concentration of potential impacts within the country.

Data Analysis: How Individual Dams Have Changed Downstream Flow Regime

Finally, to meet the third research objective, discharge records before and after dam construction were evaluated for changes at selected dams. The dams were chosen to represent a range of reservoir capacities and potential impacts. Analyses of discharge were similar to those performed by Chin et al. (2002). First, the daily discharges before and after dam construction were graphed for all years of record. Then, the mean daily discharge before and after dam construction was determined to calculate the percent of change following dam closure. Minimum monthly and peak annual discharges were similarly evaluated. These parameters are commonly the most affected by dams (Chin and Bowman, 2005; Erskine, 1985; Gregory and Park, 1974). These procedures provided both a graphical illustration as well as a quantification of changes to flow regimes. To determine the significance of post-dam changes, a two-tailed t-test for non-equal variance, using a confidence level of 0.05, was run for all variables analyzed (mean, minimum, and peak flows).

In addition to assessing flow changes, magnitude/frequency analysis was performed on one dam selected as being most representative. For this analysis, pre-dam and post-dam peak flows were analyzed. A partial duration series (Dunne and Leopold, 1978), was used for this analysis in order to capture a greater number of events than the annual maximum series would, and therefore increase the sample size. Therefore, all peak flows over a threshold value were used. The threshold value was chosen so that at least one value from each year was used. The flows were ranked with the largest event being ranked as a 1 and the rank increased with decreasing magnitude. The recurrence interval of each peak discharge was determined using the equation:

$$T = \frac{n+1}{m}$$

Where, T = the average recurrence interval in years

n = the total number of events used in the analyses

m = the rank given to the individual event.

Magnitude frequency curves were then plotted for both pre- and post- dam periods, indicating the effect of dam construction. Results of these analyses are then compared with those from temperate regions.

CHAPTER V

RESULTS AND DISCUSSION

Spatial Distribution of Dams

The International Commission on Large Dams, which maintains the World Register of Dams, defines a large dam as one that is over 15 meters high or is between 10 and 15 meters if it meets one of five conditions: a) reservoir capacity greater than 1,000,000 m^3 b) crest length at least 500 m c) maximum flood discharge dealt with by the dam at least 2,000 m^3 d) special foundation problems e) unusual design (International Commission on Large Dams, 1977). Using these criteria, 10 large dams are currently in Costa Rica (table 1; figure 10). Seven of these dams have a height greater than 15 meters: Angostura, Arenal, Cachí, Corobicí, La Garita, Peñas Blancas, and Sandillal. Of the other three dams classified as large dams, Ventanas works in cascade with smaller dams, and Toro I and Toro II work in cascade with each other (Brenes O., 1998). They therefore are unusual in design. Reservoir capacities corresponding to the dams in Costa Rica ranged from 250,000 m^3 (~200 acre-feet) for Toro I and Toro II, which share a reservoir to 1,968,000,000 m^3 (~1.6 million acre-feet) for Arenal, which also has the longest crest at 1012 m (table 1). Cachí is the tallest dam with a height of 75 m. The vertical distribution of dams ranges from 87 m to 1280 m. The mean elevation where a dam has been constructed is 543 m, (table 1).

Table 1.
Description of large dams in Costa Rica

Dam	Date Completed	Reservoir Capacity (m^3)	Dam Height (m)	Dam Length at Crest (m)	Elevation (m)	Purpose
Angostura	Oct 2000	10,900,000	36	235	577	Electricity
Arenal	Dec 1979	1,968,000,000	65	1012	499	Electricity, Irrigation
Cachí	May 1966	51,000,000	78.5	148	975	Electricity
Corobicí	Mar 1982	111,000	19	124.75	130	Electricity, Irrigation
La Garita	Apr 1958	603,458	18.75	59	453	Electricity
Sandillal	Nov 1992	5,130,000	45	270	87	Electricity, Irrigation
Toro I	Oct 1995	-	11	20	1280	Electricity
Toro II	Oct 1995	250,000	14	15	658	Electricity
Ventanas	Jul 1987	659,000	10	54	567	Electricity
Peñas Blancas	Aug 2002	2,000,000	46	203	208	Electricity

*Reservoir capacities are the “active” or “live” capacities as opposed to the gross capacity of the reservoir. This is the water that is actually trapped and released and is a more accurate volume to use for impact (Dynesius and Nilsson, 1994).

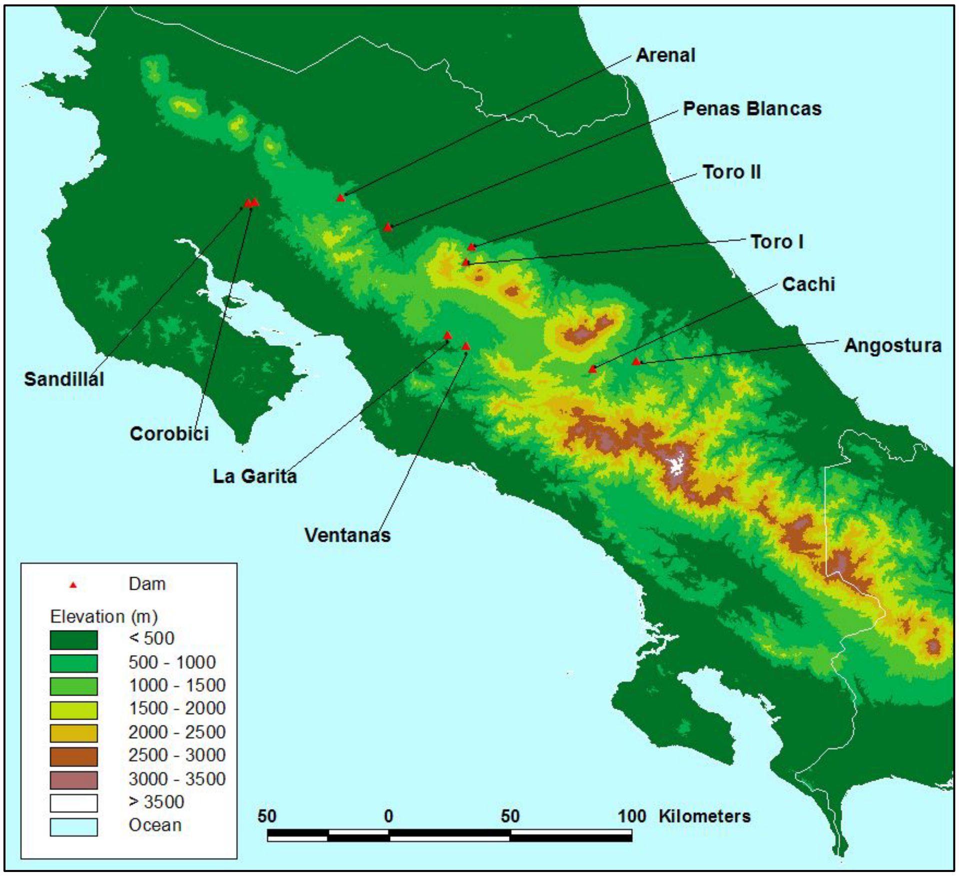


Fig. 10. Spatial distribution of the large dams in Costa Rica.

To compare the distribution of dams in Costa Rica to that in the United States, the density of dams (dams per unit area) was calculated (Table 2). This comparison is more useful since Costa Rica is much smaller than the United States, thus a comparison based strictly on the number of dams is not informative. Costa Rica, taken as a whole, averages one dam every 5112.4 km^2, a much lower density then anywhere in the United States, where density ranges from one dam every 43 km^2 in the New England area to one every 810 km^2 in the Lower Colorado River region. These results support the hypothesis that there would be fewer dams in Costa Rica compared to an equivalent area in the United States. This is likely a function of the comparatively recent trend in dam-building in tropical areas, including Costa Rica.

To determine if Costa Rica is following the same trend as other tropical areas where dam building is currently on the rise, the temporal distribution of dam closure was examined. Construction of large dams in Costa Rica began in 1958 when La Garita was closed and began operation (table 1). Dam development continues today, with the most recent dam closure being Peñas Blancas in 2002 (table 1). The temporal distribution of this construction reveals an increasing number of dams being built since 1990 (figure 11a). This follows the pattern seen worldwide of increased dam-building in tropical regions (Brandt, 2000). The trend in Costa Rica contrasts with the United States where dam building peaked in the 1960’s with the construction of 18,833 dams and has seen only a relatively few number of dams built since the mid 1980’s (Graf 1999) The cumulative reservoir capacity of the United States illustrates this trend in dam-building (figure 11b). Therefore, whereas in the United States dam construction has decreased as

Table 2.
Dam density in Costa Rica and several regions in the USA

Region	Density of Dams (dams per km2)	Area per dam (km2 per dam)
Costa Rica	0.0002	5112.4
Lower Colorado (USA)	0.0012	810
Rio Grande (USA)	0.0021	480
Pacific Northwest (USA)	0.0028	351
Upper Mississippi (USA)	0.0091	110
Lower Mississippi (USA)	0.0141	71
Mid-Atlantic (USA)	0.0164	61
New England (USA)	0.0233	43

Note: All data for regions in the United States of America (USA) were obtained from Graf (1999)

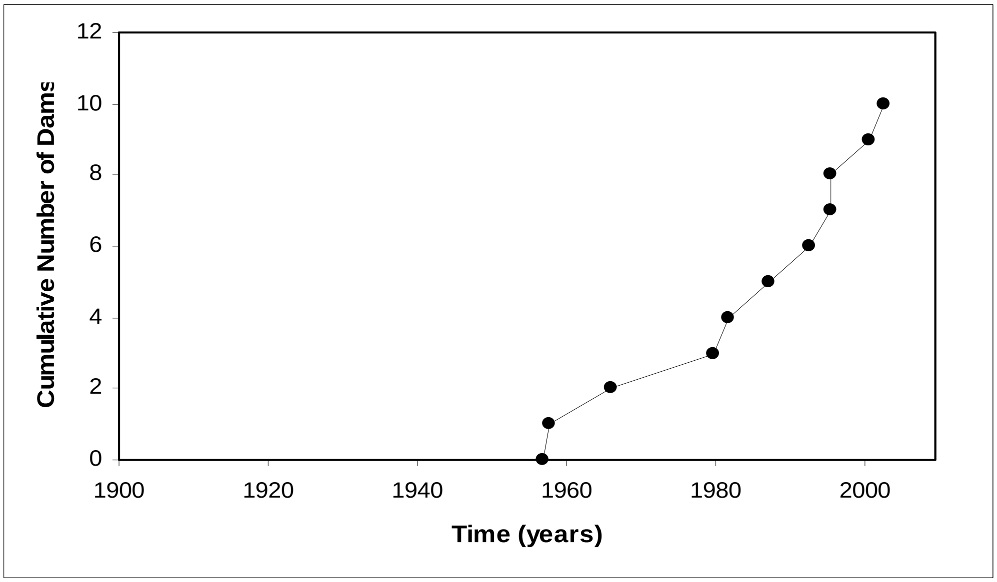


Fig. 11a. Cumulative number of large dams over time in Costa Rica.

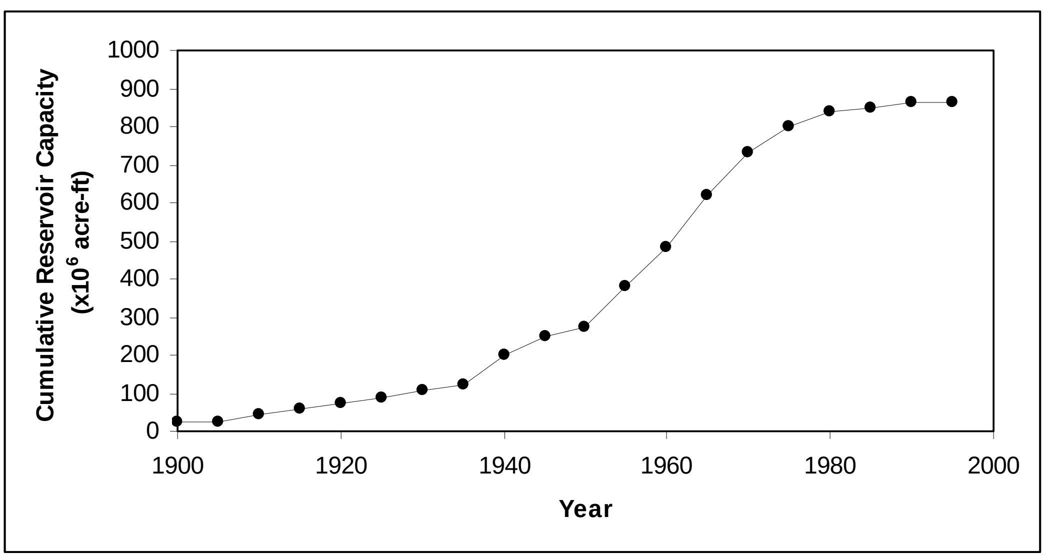


Fig. 11b. Cumulative reservoir capacity of dams in the United States. Modified from Graf (1999).

impacts are being documented, and in fact a trend of dam retirement has emerged (Pohl, 2002), Costa Rica and other tropical areas have apparently not had time to adequately study these impacts. Lessons learned from the United States and elsewhere may enable more informed dam construction and management decisions in Costa Rica and other tropical regions.

It was hypothesized that there would be a strong relation between hydroclimate and dam location. However, data suggest that hydroclimate is not the primary factor for selecting dam location. The spatial distribution of the dams shows no apparent pattern in relation to hydroclimate created by the volcanic ridge. There are 6 dams on the eastern, windward side of the volcanic chain (Angostura, Arenal, Cachí, Peñas Blancas, Toro I and Toro II) and 4 on the leeward side (Corobicí, La Garita, Sandillal, and Ventanas) (figure 10). Although there is a drier climate on the leeward side of the ridge, precipitation is still significant for several months out of the year, allowing for plenty of water to generate hydropower. However, no large dams are found in the southern third of the country despite a wetter climate (figures 2 & 10).

Land Use/Land Cover Within Basins

Whereas the overall spatial distribution revealed no apparent pattern in relation to hydroclimate, analysis of the distribution of dams in relation to land cover showed that drainage basins containing dams are dominated by either forest or crop (figure 12 & table 3). Overall, drainage basins containing large dams were dominated by forest (53.3% of the total area), followed by crops (39.2% of the total area). This is consistent

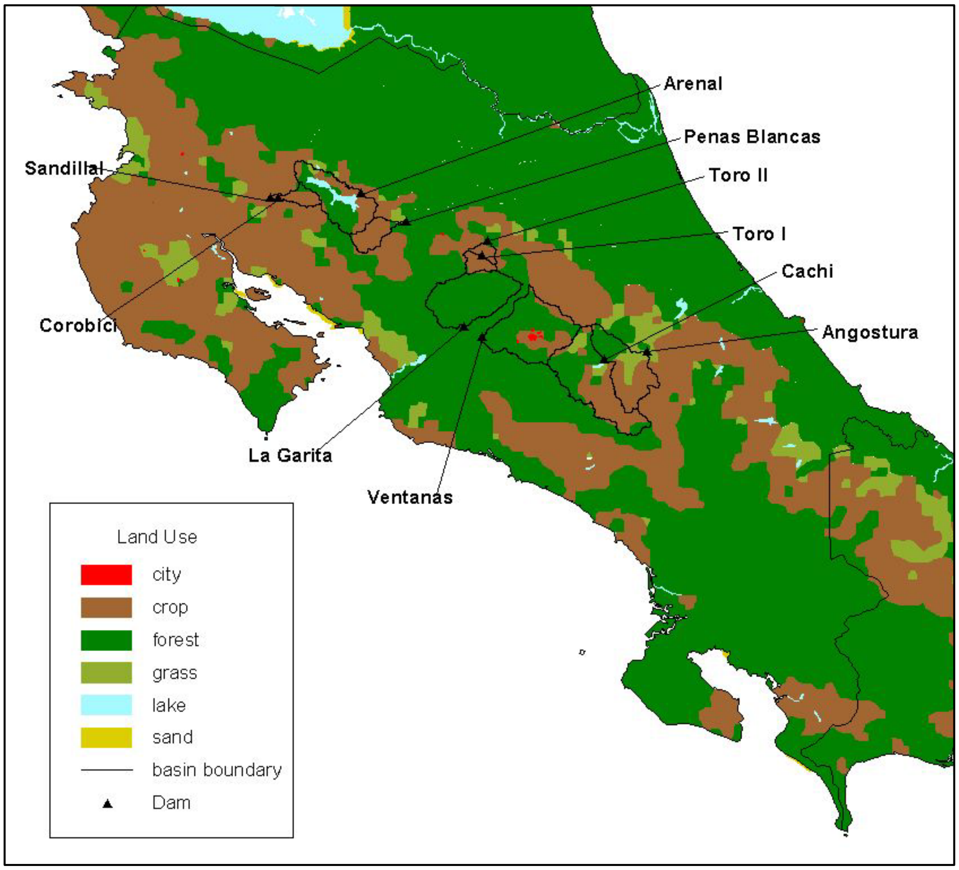


Fig. 12. Land use and land cover in Costa Rica. Land use overlaid with the drainage basins corresponding to large dams.

Table 3.
Land cover distribution for large dams

Dam	Basin Area (ha)	Tree Area %	City Area %	Grass Area %	Crop Area %
Angostura	48725	28.1	-	19.6	52.5
Arenal	50442	52.0	-	3.3	44.7
Cachí	77082	41.6	-	8.9	49.5
Corobicí	9334	16.1	-	-	83.8
La Garita	69350	91.3	0.3	6.3	2.1
Sandillal	743	-	-	-	100.0
Toro I	8170	5.0	-	-	95.0
Toro II	5642	9.2	-	-	91.1
Ventanas	75507	71.2	2.3	2.6	23.9
Peñas Blancas	16242	6.0	-	2.4	91.5
Overall	361236	53.3	0.6	6.9	39.2

with the working hypothesis that, because the country is dominated by agriculture and ecotourism, with the population concentrated in the central valley, dams would be located in areas dominated by either forest or agriculture. Land cover can be very critical to the life of a dam. In Costa Rica, Sanchez-Azofeifa and others (2002) reported that deforestation within watersheds that are used for hydropower generation leads to increased sedimentation accumulation within the reservoir and a decrease in the generation capabilities of the hydroelectric dams. Thus, analysis of land use within drainage basins containing large dams could provide insight to which dams and reservoirs may be more at risk. Because cropland increases reservoir sedimentation, conversion of forest to cropland should be avoided in basins containing large dams. Steps to prevent this have already been taken around Arenal through the establishment of Arenal National Park in 1994 around Arenal Volcano, and the protection of several thousand hectares of forest located in the Arenal watershed (Aylward et al., 1995). Additionally, sediment accumulation analysis of those basins dominated by crops (Sandillal, Toro I, Toro II, and Peñas Blancas) would be beneficial.

Surface Hydrology at a National Scale

Analysis of potential dam impacts at a large scale (defined as the equivalent of the potential reservoir storage of the dams) on the hydrology of Costa Rica reveals only a slight impact nationally. The total reservoir capacity of the large dams in Costa Rica is 2,038,653,458 m^3 (approximately 1.65 million acre-feet) (table 4). This value tells us that over 2 billion m^3 of water that is part of the surface component of the hydrologic

Table 4.
Hydrologic impacts of dams in Costa Rica

Dam	**Basin Area**	**Reservoir Capacity**	**Storage/Area**	**Storage/Annual Precipitation** (By Basin)
	km^2	m^3	$m^3\,km^{-2}$	%
Angostura	487	10,900,000	22,370	0.6%
Arenal	504	1,968,000,000	3,901,538	114.8%
Cachí	771	51,000,000	66,163	2.5%
Corobicí	93	111,000	1,189	0.1%
La Garita	693	603,458	870	0.0%
Sandillal	7	5,130,000	690,658	52.6%
Toro I	82	-	-	
Toro II	56	250,000	1,810	0.1%
Ventanas	755	659,000	873	0.0%
Peñas Blancas	162	2,000,000	12,313	0.3%
Country Total	**51,124**	**2,038,653,458**	**39,877**	**1.25%**

cycle in Costa Rica can be trapped in reservoirs. However, without comparing this to the total water available, this number is meaningless.

To get an idea of the magnitude of impact that storage causes, the total storage of the country was compared to the area of Costa Rica. Graf (1999) described this ratio as giving a “gross measure of the potential magnitude of potential change in river flows”. In other words, it gives an indication as to the potential degree of fragmentation of the rivers thereby providing a basis for analyzing potential impacts of the dams on the hydrologic regime. For Costa Rica, this ratio of total storage to land area is 39,877 m^3km^{-2} (table 4). This is a value closest to the arid Great Basin region of the United States, which is the area with the lowest ratio in the United States (Graf, 1999) (table 5). Therefore, Costa Rica compared to the majority of the United States has a lower storage to area ratio, implying that the impact of reservoir storage is relatively low.

To characterize the impact of dam storage, the ratio of storage to annual precipitation was calculated (table 4). Overall, dams in Costa Rica capture only 1.25% of the annual precipitation. Ideally, average annual runoff data (which were unavailable for these analyses) would be used to estimate potential impacts of reservoir capacity on surface water hydrology. Using precipitation as a surrogate fails to take into account the interception component of the hydrologic cycle. However, even if a very high interception rate of 50% were assumed, reservoir storage in Costa Rica would only trap 2.5% of the annual runoff. This illustrates the relatively low potential impact of reservoir storage on the surface component of the hydrologic cycle currently in Costa Rica at a large scale. This is consistent with the hypothesis that overall hydrologic

Table 5.
Reservoir storage to drainage area ratios from regions in the USA

Region	Storage/Area	
	(m^3 per km^2)	(Acre-feet per mi^2)
Great Basin	26,300	55
Great Lakes	66,300	139
Rio Grande	75,600	159
Mid-Atlantic	83,300	175
Upper Mississippi	111,500	234
Missouri	149,100	313
Upper Colorado	197,100	414
Lower Mississippi	223,700	469
Texas-Gulf	256,200	538
South Atlantic-Gulf	345,800	725

Source: Graf, 1999

impacts of dams in Costa Rica are less than those in the United States, primarily because of overall higher precipitation values in Costa Rica, which results in a lower proportion of available water being affected by dam storage.

While overall, reservoir storage impacts hydrology only minimally in Costa Rica, consistent with the hypothesis posed, analysis of individual basins showed that two dams have a disproportionately significant impact on the hydrology within their basins. Arenal Dam and Sandillal Dam have storage capacities equaling ~115% and 52.6% (respectively) of the mean annual precipitation within their basins (table 4). The two dams are located on either side of the volcanic ridge in the northern part of Costa Rica (figure 11). The other eight dams (aside from Arenal and Sandillal) store water equaling 0-2.5% of the mean annual precipitation within their basins. Thus, they are comparatively insignificant based on this criterion.

The reservoir storage created by Arenal Dam approaches 2 billion cubic meters (table 1). This is 4 times the volume of the next largest reservoir. Therefore, it is not surprising that Arenal impacts its drainage basin more significantly than the other dams based on reservoir storage. Drainage area corresponding to Sandillal Dam is 743 hectares, the smallest analyzed in this study, however the reservoir capacity of 5.1 cubic meters ranks 4th (table 1). Additionally, Sandillal Dam is located in the Northwest, which is the driest area of the country (figure 2). The combination of all of these factors explains the profound impact that Sandillal Dam has on the hydrology of the drainage basin.

Aside from Arenal and Sandillal Dams, regional impacts of reservoirs are minimal. Reservoirs capture only a small percentage of the annual precipitation within their basins. Therefore the hypothesis that reservoir impacts on hydrology are less in the tropics because of the higher total precipitation seems correct. It was also hypothesized that reservoir impacts would be greater in the eastern half of the country because it was expected that there would be more dams there because of a wetter hydroclimate. However, the distribution of impacts within Costa Rica shows no relation to the volcanic ridge, but rather impacts are concentrated in the northern part of the country with Arenal and Sandillal Dams, owning to a combination of factors including larger reservoir capacity and a drier climate in this area.

Changes in Flow Regime

Analysis of discharge data downstream of selected dams representing a range of reservoir impacts provided further details of impacts of dams in Costa Rica. Because the ratio of reservoir storage compared to annual precipitation within individual basins was found to be significant for both Arenal and Sandillal Dams, both of these dams were analyzed along with Corobicí (figure 13). Corobicí was chosen because it works in conjunction with Arenal and Sandillal in a cascading design that pipes water from one reservoir to the next. The ultimate purpose of this cascading dam design is to both produce electricity as well as provide irrigation to the northwestern portion of the country. The design begins with Arenal Dam, which closed in 1979, cutting off water supply to the downstream Arenal River that flows toward the Pacific. Rather than

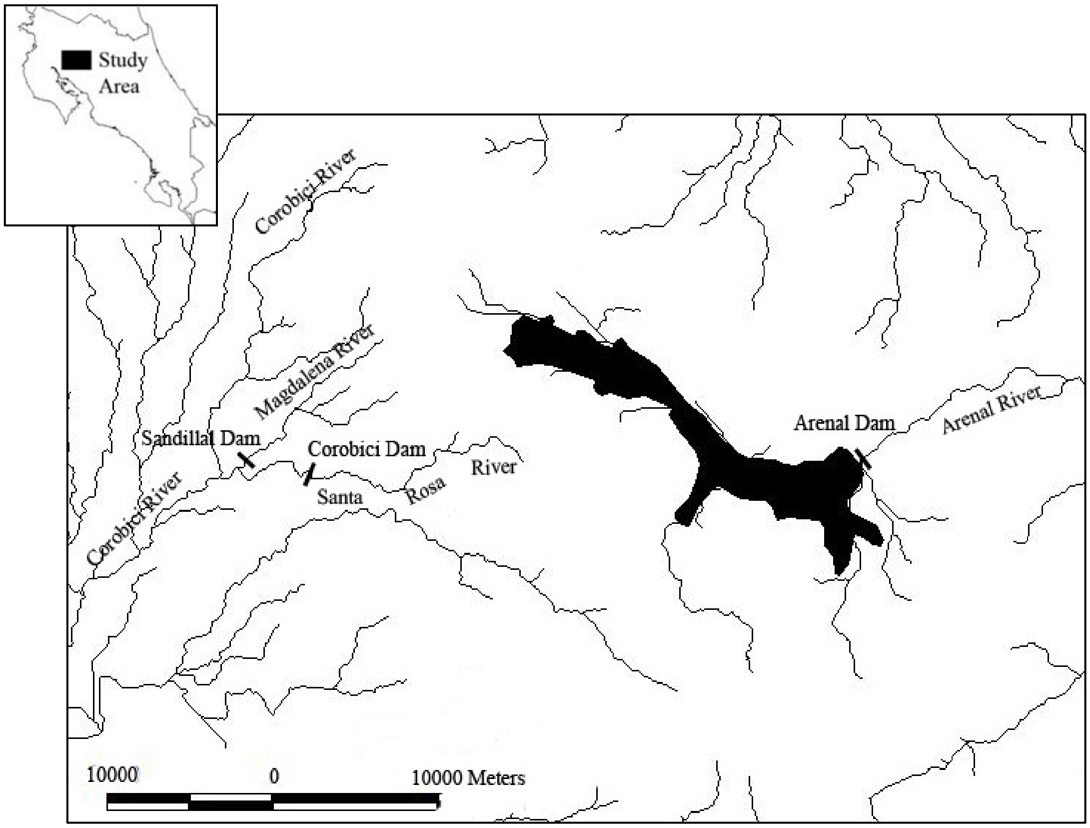


Fig. 13. Map of Arenal Dam, Corobicí Dam, and Sandillal Dam locations.

releasing water downstream of the dam, waters are redirected toward the Atlantic side of the country via a large pipe that delivers water to the Corobicí reservoir (figure 13) (Granados Calderón, 2005). These waters are used for hydroelectric production, and then are piped from Corobicí to the Sandillal Reservoir. The waters are used at Sandillal to produce electricity, and then some water eventually leaves via two channels going to the south and to the west for irrigation in the Northwestern part of the country, and other waters are released downstream of Sandillal Dam into the Magdalena River which flows toward the Pacific Coast.

For these three dams, using reservoir capacity as an indication of impact may not be as informative as streamflow analysis because of the engineering complications. Because they work in cascade, with water being piped from one reservoir to the next, all three dams impact hydrology in the Corobicí and Sandillal drainage basins. Therefore, all three were considered for streamflow analysis. Ventanas dam was further chosen as an additional and contrasting dam having less impact (based on previous results) for comparison (Table 4, Figure 10).

Arenal Dam

ICE maintained a gauging station (Estación 14-3 Sangregado) approximately 500 meters downstream of the site where Arenal Dam was constructed. This station was maintained from June 1965 until August 1978 when ICE discontinued the gauging because of construction of Arenal Dam (Granados Calderón, 2005). Data from this station provide a mean daily discharge of 48.0 cubic meters per second (cms) prior to

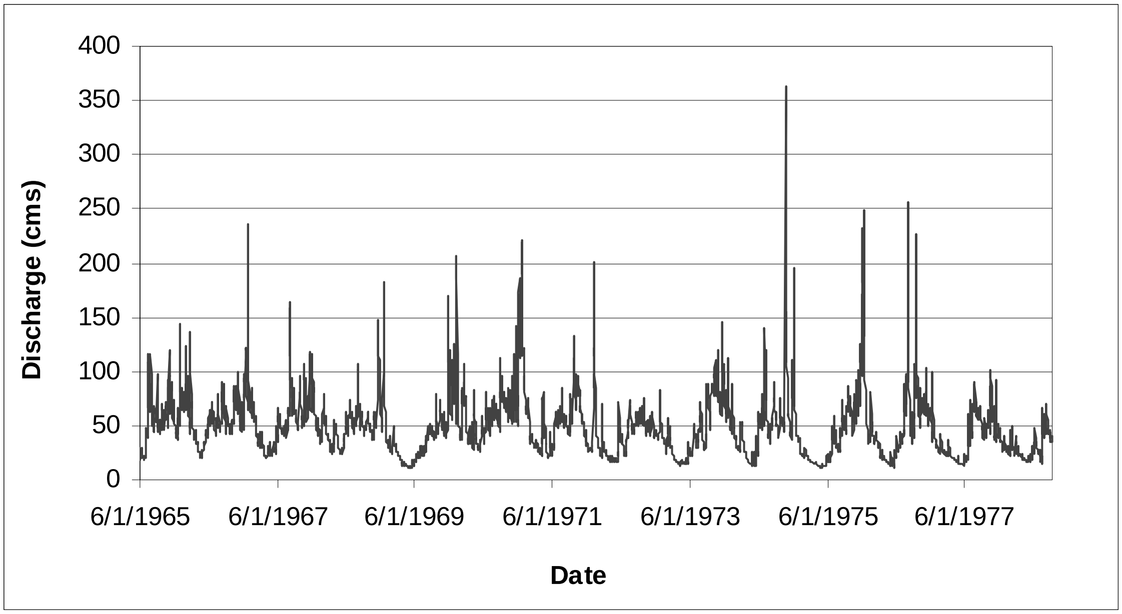


Fig. 14. Daily discharge downstream of Arenal Dam. June 1965-August 1978: Prior to closure of Arenal Dam in December 1979.

dam construction (figure 14). Peak flows during this period reached 360 cms and minimum flows were as low as 11 cms. Closure of Arenal Dam in December 1979 completely disconnected the upstream and downstream segments of Arenal River, and eliminated all upstream input. Instead of releasing flows downstream of Arenal Dam, water from the Arenal Reservoir is piped to the Corobicí Reservoir. This caused Arenal River to go dry immediately downstream of the dam (Granados Calderón, 2005).

While it was hypothesized the mean discharge would decrease, the expectation was that the decrease in downstream flow would be smaller than decreases seen in temperate regions. Because of the engineering and redirection of flow associated with Arenal Dam, not only did discharge decrease in this case, but it was completely eliminated. The effect here has been a change from a perennial river to an ephemeral one. Further investigation is needed to determine the distance downstream of the dam at which the stream recovers a permanent flow, assuming precipitation is eventually enough downstream to produce a permanent flow. Undoubtedly the changes in the downstream hydrology have implications for the geomorphology and ecology of the river, and these changes downstream need to be addressed to determine the full impact of this dam.

Corobicí Dam

By design, no water is released downstream from Corobicí Dam on a regular basis. However, occasional releases do occur (Granados Calderón, 2005). The majority of the water leaving Corobicí Dam is piped to the reservoir of Sandillal Dam for further hydroelectric production, as well as irrigation. Discharge data from a gauging station (Estación 20-04 Tilarán) located 11 kilometers downstream of Corobicí Dam on the Santa Rosa River was evaluated to determine the impacts of Corobicí Dam on downstream hydrology. Data for this station were available from September 1971 to October 2004. For evaluation, the data were divided into three time periods: (1) before December 1979 when Arenal Dam was closed, (2) December 1979 – March 1982 when Corobicí was constructed, (3) April 1982 –present. Mean daily discharge for the three time periods are 2.2, 40.5, and 2.76 cms, respectively (figure 15). The most noticeable change in mean discharge occurred during the period following closure of Arenal Dam until closure of Corobicí Dam (time period 2). Mean discharge increased during this period to more than 18 times the unregulated streamflow. The drastic increase was caused by the redirection of water from the Arenal reservoir into the Santa Rosa River. After the closure of Corobicí Dam and the associated piping of water from Corobicí Reservoir to Magdalena River (where Sandillal Dam was later constructed) downstream discharge decreased, to a mean of 2.76 cms, approaching pre-dam averages. More recently (since around the year 2000), daily discharge has been more variable (figure 15). Personal communications with an engineer at ICE elucidated that the cause of the increased downstream flow is a result of maintenance on Corobicí Dam (Granados Calderón, 2005). During this time, the dam was not working at full capacity, and waters were released into the Santa Rosa River resulting in a more natural flow regime during the past five years (Granados Calderón, 2005).

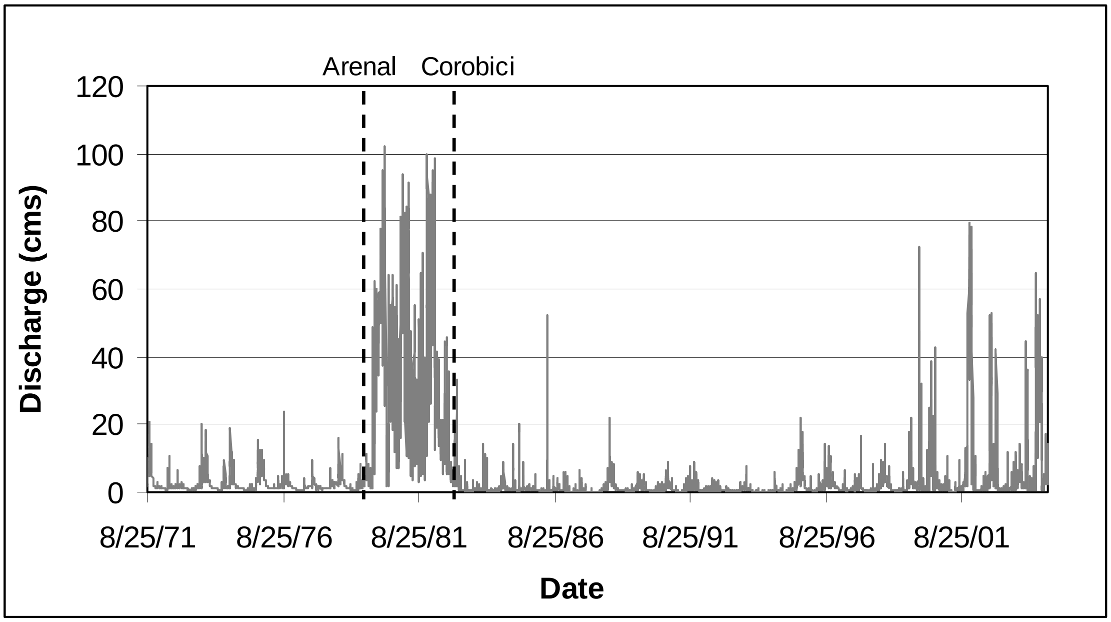


Fig. 15. Daily discharge downstream of Corobicí Dam. Lines indicate closure of Arenal and Corobicí Dams, respectively.

Analysis of minimum monthly flows again shows three distinct periods (figure 16). Prior to any regulation, the mean minimum monthly flow downstream of Corobicí Dam was 1.3 cms. When Arenal Dam began diverting water to the Santa Rosa River in 1979, mean minimum monthly discharge increased to 15.1 cms. Closure of Corobicí Dam decreased mean minimum monthly flow to 0.9 cms, only 70% of the original mean. Therefore, contrary to the normal trend of increased minimum flows following dam closure (e.g. Chin and Bowman, 2005), the effect of Corobicí Dam, in conjunction with Arenal and Sandillal, has been a decrease in minimum monthly flows since the closure of Corobicí Dam. This is a direct result of the majority of the water being piped from Corobicí Dam to the Sandillal reservoir rather than releasing the water downstream.

Assessment of peak annual discharge again reveals changes in downstream hydrology resulting from both dam closures (figure 17). Unregulated mean annual peak discharge was 16.4 cms. Diversion of water following closure of Arenal Dam increased mean annual peak flows to 87.3 cms. However, following impoundment by Corobicí Dam peak annual flows decreased to 27.9 cms. Based on these calculations, it appears that, overall, peak discharges have actually increased by 70% downstream of Corobicí Dam compared to unregulated flows prior to 1979. However, because it is known that from 2000-2004 maintenance on Corobicí Dam resulted in releases downstream that are not typical of dam management, considering the mean annual peak discharge since closure of Corobicí Dam until 1999 is more useful. This time period results in a mean

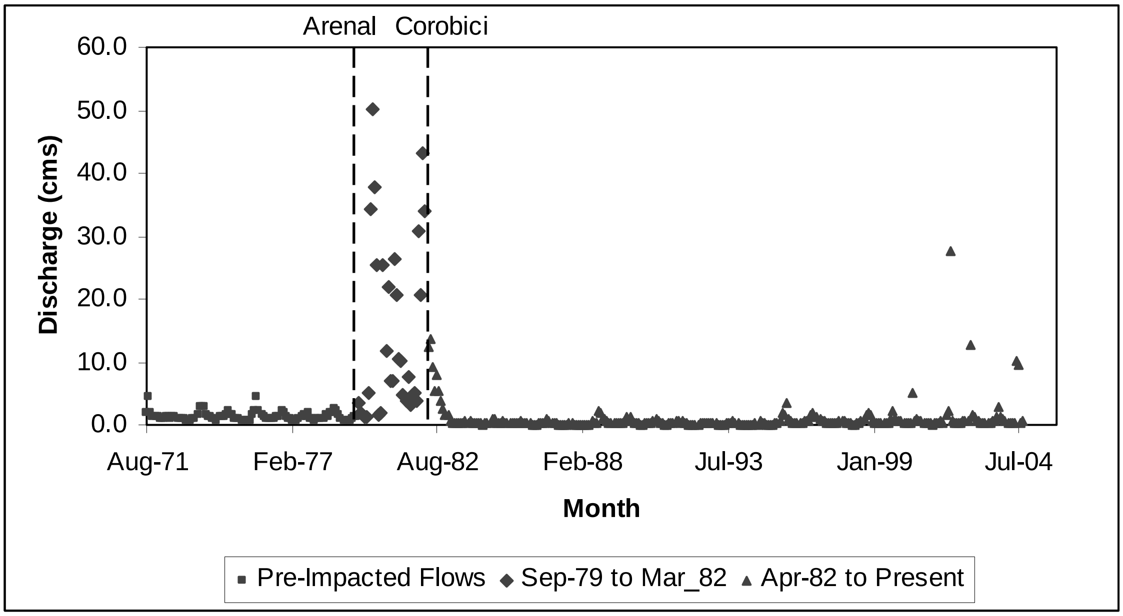


Fig. 16. Minimum monthly discharge downstream of Corobicí Dam. Lines indicate closure of Arenal and Corobicí Dams, respectively.

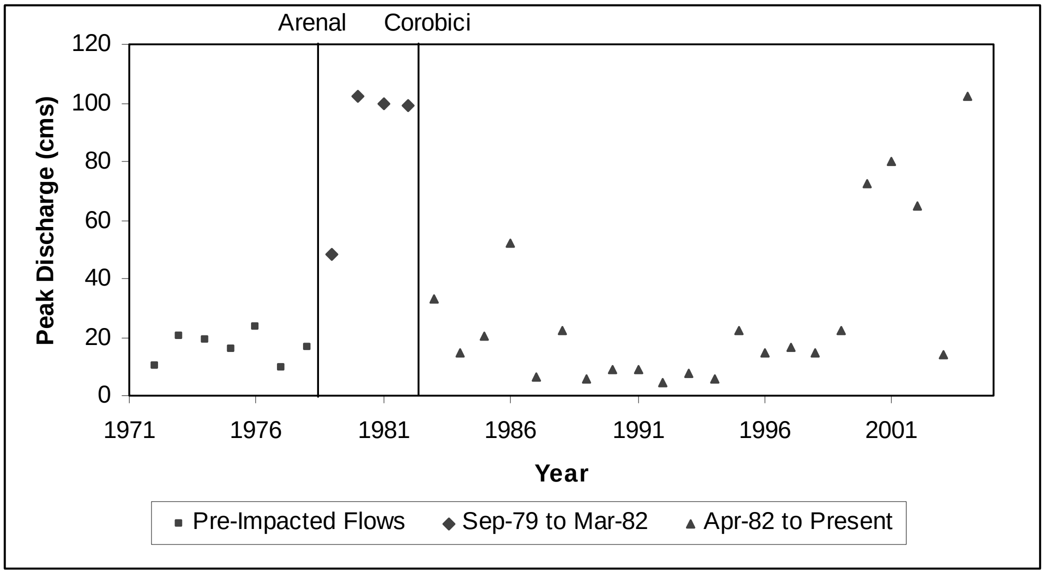


Fig. 17. Annual peak discharge downstream of Corobicí Dam. Lines indicate dam closure of Arenal and Corobicí Dams, respectively.

peak annual flow of 16.4 cms, the same mean prior to any dam impact. Therefore, based on these results, except for the years 1979-1982 when water diverted to the Santa Rosa River from the Arenal Dam was not regulated by Corobicí Dam, peak flows have remained essentially unchanged despite impoundment.

In summary, mean discharge of the Santa Rosa River, downstream of Corobicí Dam, has fluctuated drastically. A comparison of pre-regulation values (prior to construction of Arenal) with current averages (since construction of Corobicí Dam), shows both mean and minimum discharge have decreased downstream of Corobicí Dam, and peak flows have remained essentially the same with the exception of 2000-present. This is counter to the hypotheses that mean minimum flows would increase and peak flows would decrease resulting from dam closure, similar to findings in the United States (i.e. Chin and Bowman, 2005; Erskine, 1985; Gregory and Park, 1974). The redirection of water and cascading design of Arenal and Corobicí Dams clearly confound downstream trends in streamflow. However, it is evident that currently, annual peak flows remain unchanged downstream of Corobicí Dam despite the fact that water is not regularly released from the dam (instead it is piped to Sandillal Reservoir). An explanation for this could be that overland flow may be primarily derived from areas downstream of the location of Corobicí Dam (upstream of the gage). Therefore, the impacts of Corobicí Dam does not impact downstream flow as significantly as if overland flow prior to dam construction was derived primarily further upstream.

While peak flows remain close to pre-dam values, minimum monthly flows have decreased, which could significantly impact both the geomorphology and ecology downstream. Additionally, it is important to note that reservoir analysis could not detect the profound impacts that the Santa Rosa River has undergone, because they are primarily a function of engineering complications as opposed to reservoir storage. This highlights the importance of discharge analysis to fully understand impacts at the basin scale.

Sandillal Dam

Analysis of Sandillal Dam utilized streamflow data obtained 4 kilometers downstream from the dam. Discharge data were available from May 1954 through December 2004. The gauging station (Estacion 20-01 Corobicí) is located downstream of the convergence of both the Magdalena River and the Santa Rosa River with the Corobicí River (figure 14). Thus, effects of the Sandillal Dam on the Magdalena River immediately downstream of Sandillal Dam cannot be isolated with the available data. Therefore, the graph for daily discharge at this station show three time periods: 1) prior to December 1979 when Arenal was contructed 2) December 1979 to November 1992 when Sandillal was constructed 3) November 1992 to present (figure 18).

The most obvious and dramatic change to daily flows occurred upon closure of Arenal Dam (figure 18). Following the closure of Arenal Dam, and the corresponding redirection of flow into the Santa Rosa River, mean discharge increased from 8.7 cms to 46.2 cms. The Santa Rosa River flows into the Magdalena River prior to its confluence with Corobicí River (figure 13). Given the increase in mean discharge downstream of the Corobicí Dam at this time, it was expected that flow in the Corobicí River would

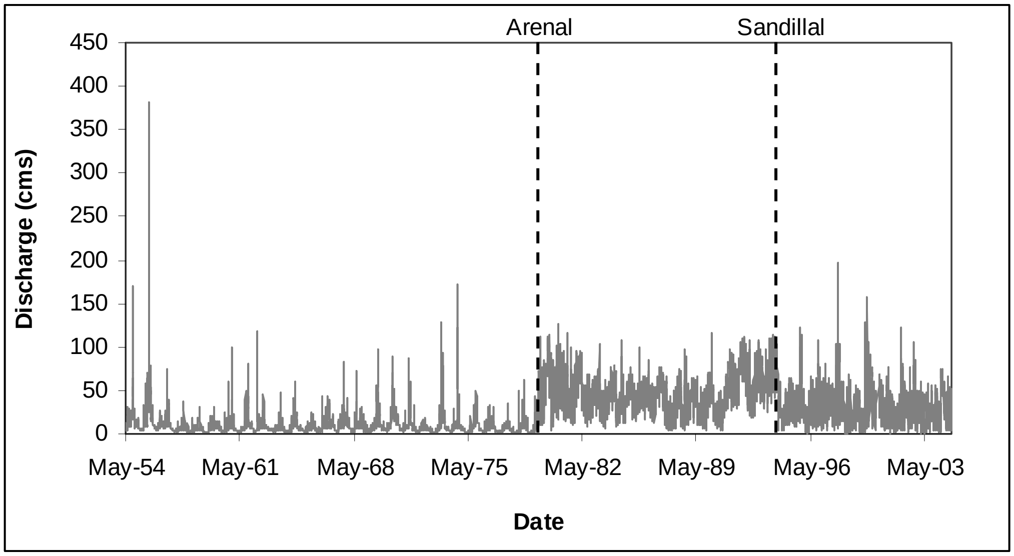


Fig. 18. Daily discharge downstream of Sandillal Dam. Lines indicate dam closure of Arenal and Sandillal Dams, respectively.

increase as well. Following closure of Corobicí Dam there was no significant change in daily discharge at the gauging station, because water that was previously reaching the gauging station via the Santa Rosa River still flowed into the Corobicí River following closure of the Corobicí Dam via the Magdalena River. This is a result of piping from the Corobicí Reservoir to the Magdalena River where Sandillal Dam would eventually be built. Closure of Sandillal Dam did result in a slight decrease of mean daily discharge. Following closure of Sandillal Dam, mean daily discharge dropped 10% to 36 cms (figure 18). The drop is attributed to some water being piped to the Northwestern part of the country for irrigation purposes. The current mean daily discharge is approximately 4 times the original, unregulated mean.

Mean minimum discharges at this site show essentially the same trend (figure 19). Mean minimum discharges corresponding to the three time periods were 5.0, 22.1, and 13.2 cms, respectively. Currently, minimum monthly discharges average 150% higher than the unregulated values. While increased minimum flows were expected based on previous results from temperate regions (e.g. Chin and Bowman, 2005; Erskine, 1985), the factors driving the increase is different in this case. Increased minimum flows in previous dam studies in the United States resulted from dam releases during periods of low precipitation (Chin and Bowman, 2005). For the situation downstream of Sandillal Dam, increased flows derive from redirection of water from the Arenal Dam on the Pacific side of the volcanic ridge for the dual purposes of production of electricity and irrigation. Thus, human activities contribute to the trend in downstream flows.

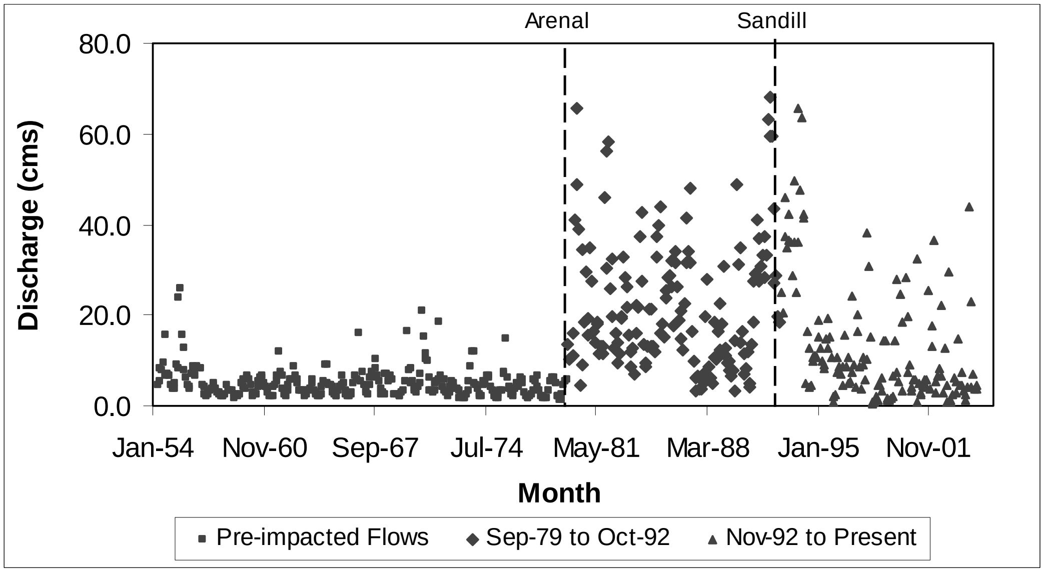


Fig. 19. Minimum monthly discharge downstream of Sandillal Dam. Lines indicate dam closure of Arenal and Sandillal Dams, respectively.

Analysis of annual peak discharge from 1954–2004 shows increased mean peak discharge during each time period (figure 20). Prior to construction of Arenal Dam and the subsequent redirection of water, the mean peak annual discharge was 82.3 cms. Following closure of Arenal Dam, the mean increased to 101 cms, and since closure of Sandillal Dam, mean annual peak discharges have been 114 cms. Evaluation at a smaller time scale provides a slightly different trend. Mean monthly peak discharges for the three time periods were 22.7, 69.6, and 62.7 cms, respectively. Both time scales reveal an overall increase in peak discharges, which can be attributed to the overall increased water supply following closure of Arenal Dam.

Overall, results for Corobicí River downstream of the Sandillal Dam are counter to the expectation based on temperate studies (e.g. Chin and Bowman, 2005; Erskine, 1985; Gregory and Park, 1974). While reservoir storage analysis suggested that Sandillal Dam would have a major impact on the drainage basin because of its ability to store 100% of the mean annual precipitation of the basin, it in fact has only a minor effect. Overall, mean, minimum, and peak flows have all increased downstream of Sandillal Dam, despite impoundment and subtraction of water for irrigation. This is a direct result of increased water supplied by Arenal Dam and Reservoir.

Ventanas Dam

For comparison to a dam ascertained to have minimal effects regionally, and one that functions without the engineering complications of the previous three dams, discharge analyses were conducted downstream of Ventanas Dam (figure 10). Ventanas

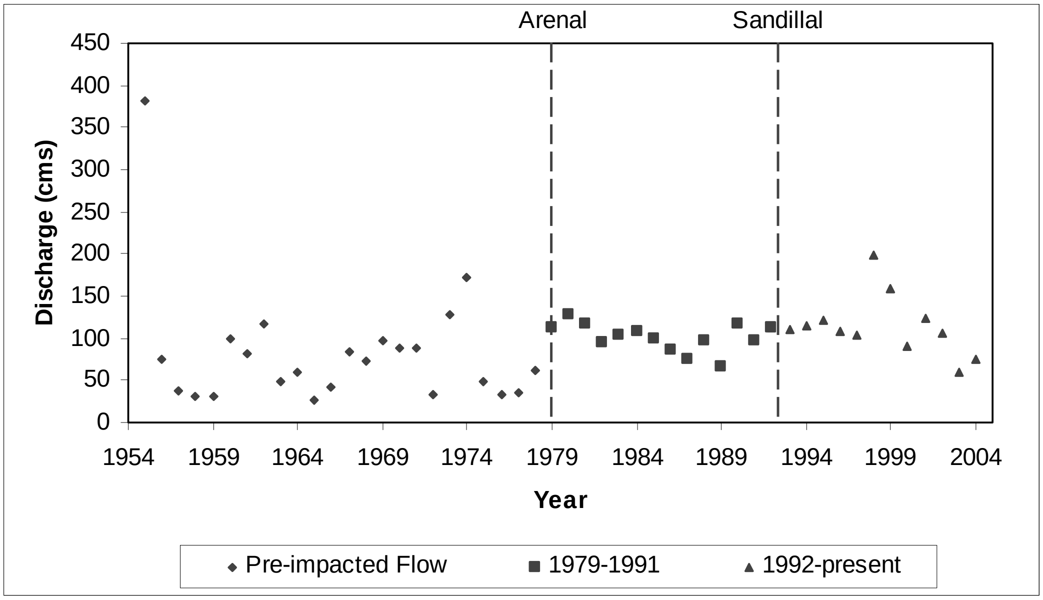


Fig. 20. Peak annual discharge downstream of Sandillal Dam. Lines indicate dam closure of Arenal and Sandillal Dams, respectively.

began operation in July 1987 (table 1). Discharge data were obtained at a gauging station located approximately 5 kilometers downstream of the dam (Estación 24-5 San Miguel) on the Virilla River. Figure 21 shows that mean daily discharge before and after dam construction were 35.5 and 31.4 cms, respectively. Mean minimum discharge also decreased slightly, from 21.8 to 20.0 cms (figure 22). These values represent an 11.5% and an 8% decrease, respectively. Using a two-tailed t-test, assuming unequal variance, the change in mean daily discharge was found to be statistically significant at a confidence level of 0.05. The slight decrease in minimum discharge was not found to be statistically significant using the two-tailed t-test.

Additionally, peak discharges decreased at both the annual and monthly scale. Mean peak annual discharge decreased from 185.5 to 124.5 cms, a 33% decrease (figure 23). At a smaller monthly scale, the decrease is only 26.3%, with mean peak monthly discharge decreasing from 74.1 to 50.0 cms. Both at the annual and monthly scales, decrease in peak monthly discharges were found to be statistically significant using a two-tailed t-test with a confidence level of 0.05 The highest discharge on record prior to construction of Ventanas Dam was 561 cms (figure 23). Since impoundment, the highest recorded discharge is 197 cms, only 35% of the highest flow prior to dam closure.

To more clearly elucidate downstream changes in streamflow resulting from Ventanas dam, further analyses were done to examine the timing of impacts as well as the change in the frequency of high flows. Dams often produce a more equitable flow regime, decreasing the seasonal fluxes (e.g. Chin and Bowman, 2005). To assess

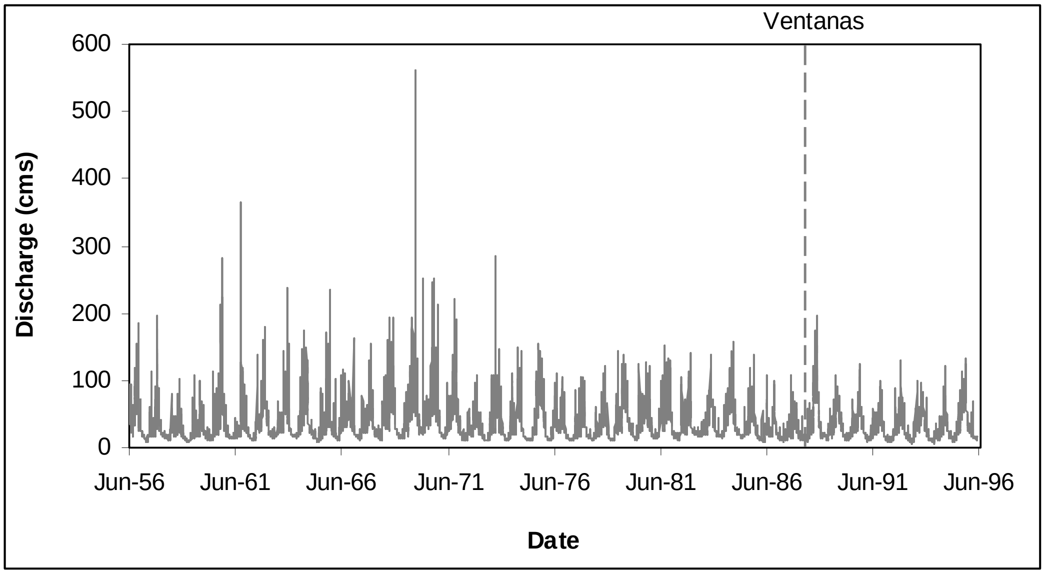


Fig. 21. Daily discharge downstream of Ventanas Dam. Line indicates dam closure.

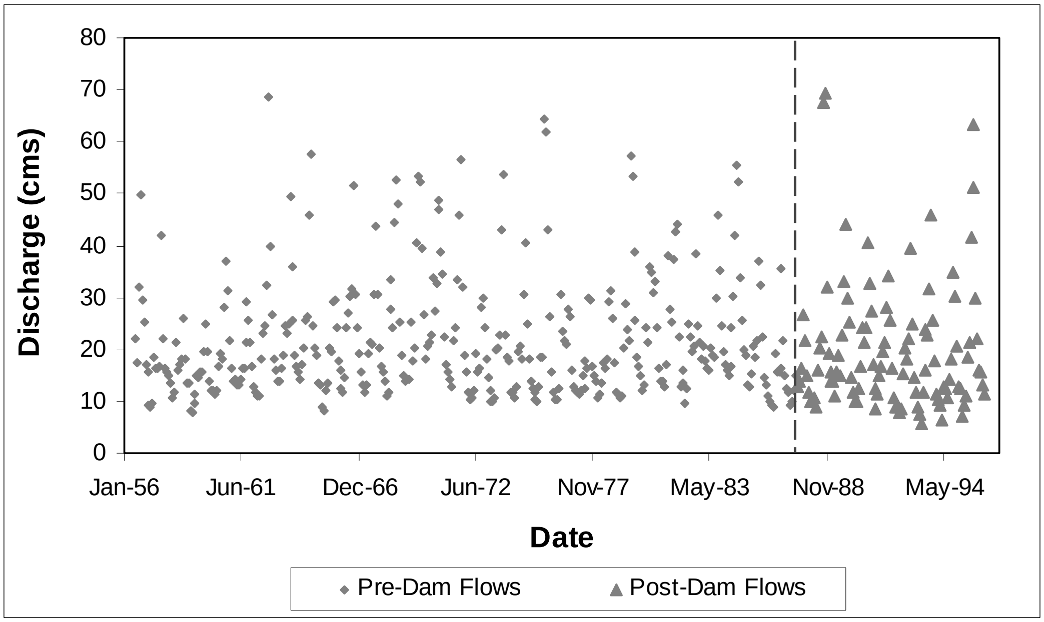


Fig. 22. Minimum monthly discharge downstream of Ventanas Dam. (line indicates dam closure).

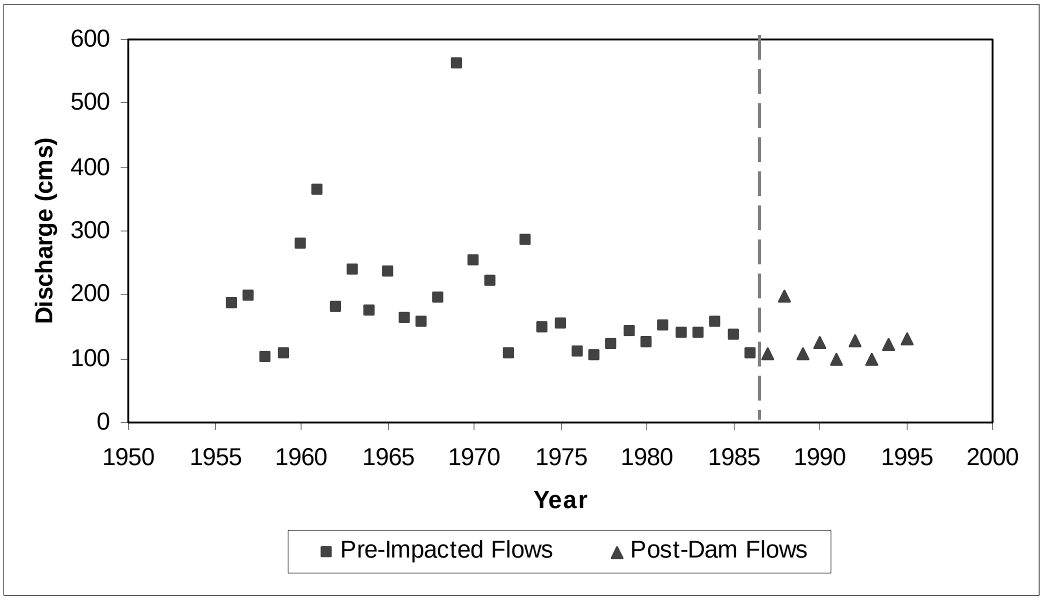


Fig. 23. Annual peak discharge downstream of Ventanas Dam. (line indicates dam closure).

whether the same trend occurs in Costa Rica, average total monthly flow before and after dam closure was calculated (figure 24). While mean daily, mean minimum monthly, and mean annual peak discharges all decreased subsequent to dam closure, there is no apparent seasonal effect. This is probably a result of year-round precipitation, despite more ubiquitous rainfall from August to December, in contrast to temperate regions that do not have year-round precipitation. Overall total monthly discharge has stayed within pre-dam ranges (figure 24).

For the magnitude/frequency analysis a threshold value of 100 cms provided at least one peak discharge per year for the partial duration series (table 4 and table 7). This provided a larger sample size of events, which was especially important for post-dam analysis because only 10 years of data were available after dam closure. Results of the magnitude/frequency analysis downstream of Ventanas Dam show a decrease in frequency of high magnitude discharges (figure 25). A logarithmic regression line was fitted to both pre-dam and post-dam data. The regression line corresponding to the period following dam closure shows a decreased slope compared to pre-dam results, illustrating the decrease in the magnitude of peak discharges resulting from closure of Ventanas Dam (figure 25). In fact, since dam closure no discharge events over 200 cms have occurred. Prior to closure of Ventanas Dam, the highest event was 561 cms, over 2.5 times the post-dam maximum discharge (table 6 and table 7). Furthermore, even smaller peaks show a marked decrease in frequency. For example, prior to dam construction a discharge of 145 cms occurred approximately every 5 years, however,

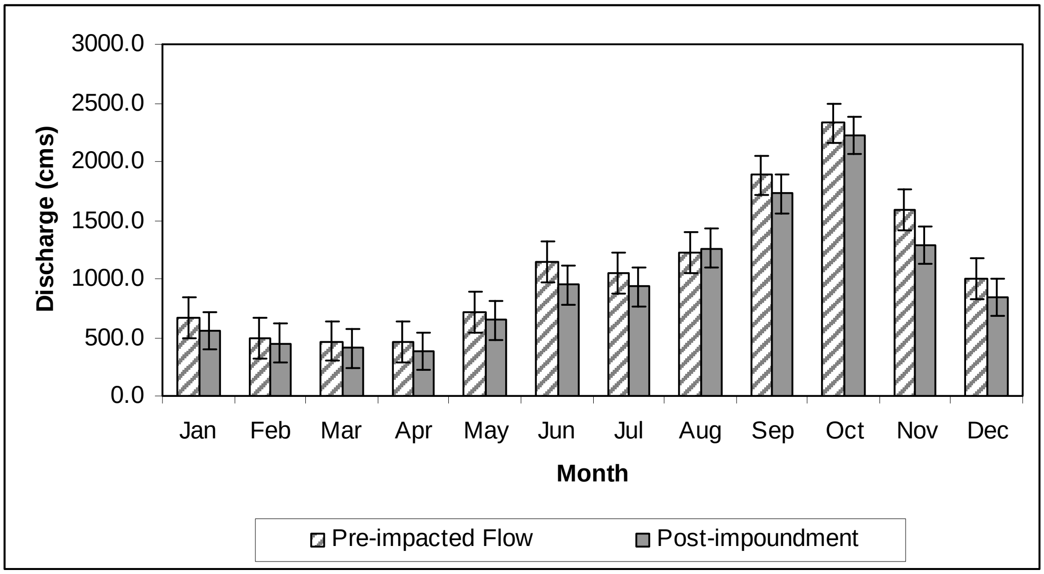


Fig. 24. Average total monthly discharge downstream of Ventanas Dam.

Table 6. Discharge events over 100 cms prior to closure of Ventanas Dam

Date	Discharge (cms)	Date	Discharge (cms)	Date	Discharge (cms)	Date	Discharge (cms)
Sep-1956	109	Sep-1961	105	Sep-1964	105	Sep-1968	126
Sep-1956	114	Sep-1961	107	Sep-1964	103	Sep-1968	100
Sep-1956	118	Sep-1961	107	Sep-1964	107	Sep-1968	131
Oct-1956	111	Sep-1961	127	Oct-1964	116	Sep-1968	141
Oct-1956	156	Sep-1961	114	Oct-1964	102	Sep-1968	109
Oct-1956	105	Oct-1961	118	Oct-1964	113	Oct-1968	100
Oct-1956	101	Jul-1962	138	Oct-1964	115	Oct-1968	137
Oct-1956	118	Sep-1962	112	Oct-1964	150	Oct-1968	118
Oct-1956	114	Sep-1962	158	Oct-1964	118	Oct-1968	137
Oct-1956	121	Oct-1962	108	Oct-1964	110	Oct-1968	158
Nov-1956	101	Oct-1962	125	Oct-1964	113	Oct-1968	102
Nov-1956	185	Oct-1962	160	Oct-1964	130	Nov-1968	109
Jul-1957	114	Oct-1962	115	Oct-1964	110	Nov-1968	123
Sep-1957	116	Oct-1962	105	Oct-1964	100	Nov-1968	194
Sep-1957	121	Oct-1962	112	Sep-1965	103	Nov-1968	113
Sep-1957	197	Oct-1962	110	Sep-1965	110	Nov-1968	103
Sep-1957	147	Oct-1962	130	Sep-1965	172	Nov-1968	105
Sep-1957	101	Oct-1962	137	Sep-1965	140	Aug-1969	122
Sep-1957	115	Oct-1962	112	Sep-1965	112	Aug-1969	108
Sep-1957	147	Oct-1962	105	Oct-1965	118	Aug-1969	104
Sep-1957	141	Oct-1962	112	Oct-1965	134	Aug-1969	113
Sep-1957	101	Oct-1962	171	Oct-1965	103	Sep-1969	141
Oct-1957	125	Oct-1962	136	Oct-1965	154	Sep-1969	103
Oct-1957	101	Oct-1962	103	Oct-1965	129	Sep-1969	119
Oct-1957	133	Oct-1962	137	Oct-1965	103	Sep-1969	158
Oct-1957	158	Oct-1962	115	Nov-1965	104	Sep-1969	116
Oct-1957	178	Oct-1962	103	Nov-1965	235	Sep-1969	100
Oct-1957	141	Nov-1962	131	Nov-1965	101	Sep-1969	137
Oct-1958	102	Nov-1962	181	Feb-1966	101	Sep-1969	115
Oct-1958	102	Nov-1962	158	Jun-1966	107	Sep-1969	172
Jun-1959	107	Nov-1962	129	Jul-1966	117	Sep-1969	177
Oct-1959	100	Nov-1962	104	Aug-1966	111	Sep-1969	138
May-1960	107	Nov-1962	149	Dec-1966	164	Oct-1969	103
May-1960	114	Sep-1963	109	Sep-1967	112	Oct-1969	129
Aug-1960	111	Sep-1963	125	Sep-1967	101	Oct-1969	171
Oct-1960	213	Sep-1963	129	Sep-1967	118	Oct-1969	141
Oct-1960	157	Sep-1963	110	Oct-1967	109	Oct-1969	124
Oct-1960	281	Sep-1963	123	Oct-1967	104	Oct-1969	193
Oct-1960	178	Sep-1963	145	Oct-1967	129	Oct-1969	185
Oct-1960	108	Sep-1963	120	Oct-1967	125	Oct-1969	148
Oct-1960	107	Oct-1963	114	Oct-1967	104	Oct-1969	123
Oct-1960	101	Oct-1963	106	Oct-1967	126	Oct-1969	163
Oct-1960	104	Nov-1963	107	Oct-1967	156	Oct-1969	179
Oct-1960	162	Nov-1963	126	Oct-1967	144	Oct-1969	170
Oct-1960	149	Nov-1963	238	Oct-1967	102	Oct-1969	150
Oct-1960	101	Nov-1963	192	Jun-1968	105	Oct-1969	144
Oct-1960	224	Nov-1963	109	Jun-1968	106	Oct-1969	126
Oct-1960	129	Nov-1963	113	Jul-1968	107	Oct-1969	100
Oct-1960	115	Dec-1963	154	Aug-1968	161	Nov-1969	287
Oct-1960	114	Jul-1964	104	Aug-1968	103	Nov-1969	561
Oct-1960	111	Jul-1964	120	Sep-1968	115	Nov-1969	268
Nov-1960	129	Jul-1964	116	Sep-1968	150	Nov-1969	197
Nov-1960	158	Jul-1964	146	Sep-1968	105	Nov-1969	145
Nov-1960	100	Jul-1964	104	Sep-1968	150	Nov-1969	131
Sep-1961	127	Jul-1964	124	Sep-1968	193	Nov-1969	132
Sep-1961	365	Sep-1964	175	Sep-1968	178	Dec-1969	133
Sep-1961	174	Sep-1964	140	Sep-1968	116	Jan-1970	121

Table 6 Continued

Date	Discharge (cms)	Date	Discharge (cms)	Date	Discharge (cms)	Date	Discharge (cms)
Apr-1970	169	Oct-1971	123	Nov-1975	132	Sep-1981	102
Apr-1970	251	Oct-1971	160	Nov-1975	110	Sep-1981	111
Aug-1970	122	Oct-1971	115	Nov-1975	106	Sep-1981	128
Aug-1970	131	Oct-1972	109	Dec-1975	103	Sep-1981	104
Aug-1970	135	Jun-1973	109	Dec-1975	102	Sep-1981	107
Aug-1970	247	Jun-1973	102	Aug-1976	110	Oct-1981	104
Aug-1970	105	Jul-1973	107	Nov-1976	104	Oct-1981	100
Sep-1970	148	Aug-1973	286	Nov-1976	101	Oct-1981	105
Sep-1970	107	Aug-1973	193	Sep-1977	104	Oct-1981	102
Sep-1970	131	Aug-1973	137	Sep-1977	104	Oct-1981	110
Sep-1970	103	Oct-1973	107	Sep-1977	103	Oct-1981	107
Sep-1970	111	Oct-1973	101	Nov-1977	100	Oct-1981	115
Sep-1970	102	Oct-1973	106	Sep-1978	111	Oct-1981	134
Sep-1970	111	Oct-1973	130	Sep-1978	102	Oct-1981	115
Sep-1970	139	Oct-1973	131	Oct-1978	102	Nov-1981	105
Oct-1970	137	Oct-1973	146	Oct-1978	104	Nov-1981	131
Oct-1970	103	Oct-1973	110	Oct-1978	121	Nov-1981	119
Oct-1970	112	Sep-1974	150	Oct-1978	104	Nov-1981	109
Oct-1970	103	Sep-1974	117	Oct-1978	118	May-1982	106
Oct-1970	111	Sep-1974	107	Oct-1978	115	Oct-1982	106
Oct-1970	118	Sep-1974	101	Aug-1979	105	Oct-1982	100
Oct-1970	252	Oct-1974	102	Aug-1979	124	Oct-1982	112
Oct-1970	137	Oct-1974	118	Aug-1979	103	Oct-1982	116
Nov-1970	109	Dec-1974	106	Sep-1979	107	Oct-1982	141
Nov-1970	147	Dec-1974	143	Sep-1979	139	Oct-1982	117
Nov-1970	112	Dec-1974	135	Sep-1979	107	Oct-1983	121
Nov-1970	138	Aug-1975	113	Sep-1979	119	Oct-1983	139
Nov-1970	148	Aug-1975	107	Sep-1979	108	Oct-1983	120
Dec-1970	213	Aug-1975	105	Sep-1979	113	Oct-1983	102
Dec-1970	161	Aug-1975	110	Sep-1979	104	Oct-1983	101
Dec-1970	112	Sep-1975	114	Oct-1979	107	Oct-1983	133
Dec-1970	125	Sep-1975	104	Oct-1979	125	Oct-1983	116
Dec-1970	139	Sep-1975	106	Oct-1979	104	Oct-1983	111
Aug-1971	112	Sep-1975	100	Oct-1979	103	Oct-1983	118
Sep-1971	139	Sep-1975	104	Oct-1979	104	Oct-1983	125
Sep-1971	111	Sep-1975	110	Jun-1980	124	Oct-1983	115
Sep-1971	221	Sep-1975	107	Jun-1980	120	Nov-1983	101
Sep-1971	120	Sep-1975	107	Sep-1980	106	Sep-1984	107
Sep-1971	105	Sep-1975	132	Sep-1980	121	Sep-1984	100
Sep-1971	107	Sep-1975	136	Sep-1980	113	Sep-1984	106
Sep-1971	148	Sep-1975	155	Sep-1980	126	Sep-1984	105
Sep-1971	121	Sep-1975	147	Sep-1980	121	Sep-1984	103
Sep-1971	118	Sep-1975	128	Oct-1980	106	Sep-1984	119
Sep-1971	122	Sep-1975	110	Oct-1980	104	Sep-1984	113
Sep-1971	104	Sep-1975	143	Oct-1980	105	Sep-1984	100
Sep-1971	120	Sep-1975	140	Oct-1980	125	Sep-1984	100
Oct-1971	135	Sep-1975	118	Oct-1980	108	Sep-1984	101
Oct-1971	108	Sep-1975	129	Oct-1980	103	Sep-1984	116
Oct-1971	157	Sep-1975	111	Nov-1980	111	Sep-1984	101
Oct-1971	141	Oct-1975	104	Nov-1980	104	Sep-1984	111
Oct-1971	104	Oct-1975	100	Dec-1980	121	Sep-1984	102
Oct-1971	105	Oct-1975	104	Dec-1980	110	Oct-1984	145
Oct-1971	112	Oct-1975	110	Jul-1981	109	Oct-1984	157
Oct-1971	191	Oct-1975	128	Aug-1981	128	Nov-1984	130
Oct-1971	177	Oct-1975	108	Aug-1981	151	Aug-1985	120
Oct-1971	157	Oct-1975	104	Aug-1981	111	Oct-1985	112
Oct-1971	139	Nov-1975	114	Aug-1981	111	Oct-1985	137
						May-1986	108

Table 7.
Discharge events over 100 cms after closure of Ventanas Dam

Date	Discharge (cms)
Aug-1987	106
Aug-1987	108
Aug-1988	109
Aug-1988	110
Aug-1988	123
Sep-1988	110
Sep-1988	173
Sep-1988	145
Sep-1988	108
Sep-1988	116
Sep-1988	126
Sep-1988	111
Sep-1988	102
Oct-1988	109
Oct-1988	102
Oct-1988	119
Oct-1988	112
Oct-1988	130
Oct-1988	197
Oct-1988	141
Oct-1988	152
Oct-1988	134
Oct-1988	112
Oct-1988	116
Sep-1989	108
Oct-1990	105
Oct-1990	115
Oct-1990	124
Nov-1990	103
Oct-1991	100
Oct-1992	129
Jul-1993	100
Nov-1994	123
Aug-1995	114
Oct-1995	101
Oct-1995	115
Oct-1995	120
Oct-1995	115
Oct-1995	100
Oct-1995	132
Oct-1995	107
Oct-1995	124
Oct-1995	114
Oct-1995	105
Oct-1995	119

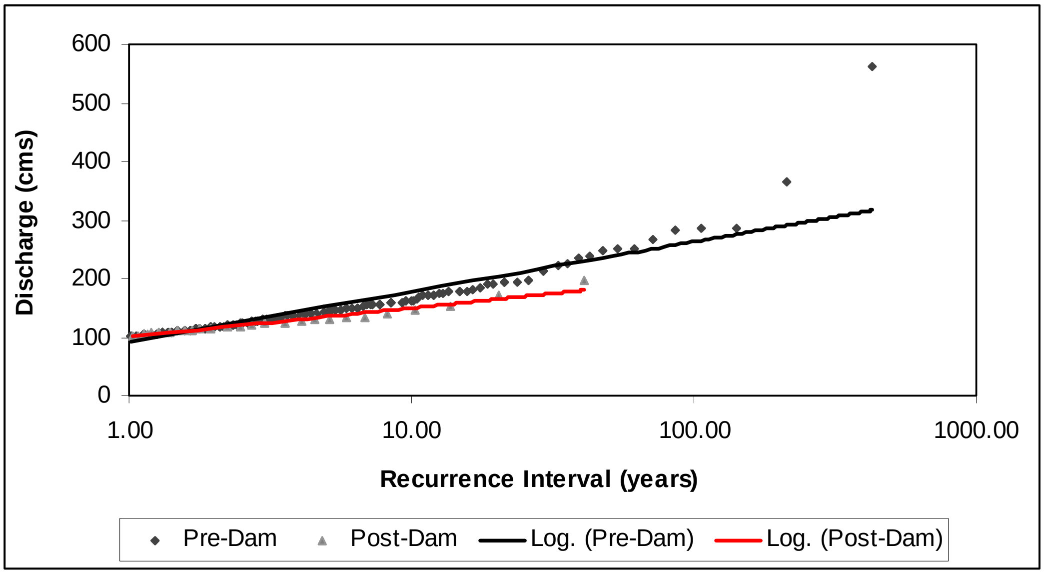


Fig. 25. Magnitude/frequency analysis of pre- and post- dam peak flows. Analysis of peak flows downstream of Ventanas Dam.

since dam construction the recurrence interval has doubled to 10 years, cutting the frequency of this magnitude in half (figure 26).

Overall, results for Ventanas Dam supported the working hypothesis that dams cause a decrease in mean and peak flows. However, it was expected that minimum flows would increase resulting from a more stable water supply, the case normally seen in temperate regions (e.g. Chin and Bowman, 2005). In the case of Ventanas Dam, minimum daily discharge decreased, although this was not statistically significant. Additional analysis of daily and monthly precipitation over the examined time period is needed to strengthen these conclusions. It is possible that lower precipitation over the past 15 years could explain the decreasing trend of mean and peak discharges observed downstream of Ventanas Dam. Further investigation into this relation is needed before more definitive conclusions can be made. Unfortunately, those data were not available at the time of this study.

Additionally, it was hypothesized that alteration of downstream flows would be to a much smaller degree than in temperate areas. Table 8 shows hydrologic changes for a variety of drainage basin sizes in temperate regions compared to those for Ventanas Dam. Mean discharge changes in temperate studies range from 0 to a 6% decrease (table 8). In contrast, mean discharge downstream of Ventanas Dam decreased by 11%, almost double the typical decrease observed. The difference between temperate environments and results of this study are more pronounced when looking at the change in changes in minimum and peak flows. All studies that reported changes in minimum flows in temperate regions reported an increase ranging from 240 – 480% (table 8).

Table 8.
Comparison of downstream hydrologic changes observed in temperate regions with those found downstream of Ventanas Dam

Dam	Drainage Area	Mean Flow Change	Min. Flow Change	Peak Flow Change
	km^2	%	%	%
Ventanas Dam	755	- 11.5	- 8	- 33
Temperate Studies				
[1]Ferrells Bridge Dam	3.44	- 5	+ 400	- 80
[2]Clatworthy Dam	15			- 60
[3]Blue River Dam	228			- 50
[4]Somerville Dam	1832	- 6	+ 480	- 85
[5]Flaming Gorge Dam	38850	no change	+ 240	- 56

[1] Winemiller et al. (2005); [2] Gregory and Park (1974); [3] Ligon et al. (1995); [4] Chin and Bowman (2005); [5] Merritt and Cooper (2000)

Rather than increasing minimum flows downstream of Ventanas Dam, impoundment decreased minimum flows by 8%. Additionally, whereas peak discharges are typically reduced by 50 – 80% according to temperate studies, peak discharge reductions resulting from impoundment fall well under this range with only a 33% reduction. Therefore, the hypothesis that downstream flow alteration would be to a smaller degree in the tropics is supported by peak discharge results, but not by changes to the mean or mean minimum discharge analyses.

Patterns seen for Ventanas Dam could be explained by the purpose served by the dam. Ventanas Dam, along with the other large dams in Costa Rica, are primarily built for the production of hydroelectric power. The majority of the dams studied in temperate regions function for the purpose of flood control. Therefore, whereas in temperate regions, water is released during low flow periods and stored during high flows to prevent flooding, in Costa Rica, excess water is not released as frequently during low flow periods. In fact, that is when water storage is more important in order to maintain a steady water supply without interruption to hydroelectric production.

CHAPTER VI

CONCLUSIONS

Summary of Findings

The first objective was to quantify the number of large dams in Costa Rica and determine their geographic distribution along with distribution in relation to land cover using GIS analysis. Results indicate that there are currently 10 dams in Costa Rica. Six are located on the Atlantic side and four are found on the leeward, Pacific side of the volcanic ridge dividing the country. While it was hypothesized that hydroclimate in Costa Rica would affect the distribution of dams in Costa Rica, there is no definitive trend in dam location in relation to hydroclimate. This is likely a result of plentiful rainfall throughout the majority of the country. Also, dam development in the drier northwestern part of the country on the leeward side of the volcanic chain (Corobicí, and Sandillal Dams) can likely be attributed to an increased need for irrigation in this primarily agricultural region (figure 13). The working hypothesis for the first objective, that there would be fewer dams in Costa Rica then in temperate environments, was supported by comparing the density of dams with areas throughout the United States. The density of dams is currently much lower than anywhere in the United States (Graf, 1999). This supports the overall hypothesis that dams in tropical areas do not impact hydrology as significantly as in temperate areas. The lower density of dams combined with higher precipitation in Costa Rica than in temperate regions helps to minimize the impacts of the dams nationally.

The second objective of this study was to analyze the impacts on hydrology created by reservoir storage. The working hypothesis was that dam storage would be minimal compared to annual precipitation, and that therefore, dams would have only a small impact on hydrology in Costa Rica. This was supported by the fact that overall, total reservoir storage for Costa Rica is only capable of impounding 1.25% of the mean annual precipitation. Even accounting for 50% interception, the dams are capable of storing only a small fraction of the available surface runoff (~2.5%). This is a much lower value than anywhere in the temperate United States (Graf, 1999). Analysis by basin revealed only two basins that contain dams with reservoirs capable of storing a significant percentage of the mean annual precipitation (Arenal and Sandillal). All other reservoirs ranged from 0-2.5% of the mean annual precipitation being able to be stored. Therefore, with the exception of the northwestern part of the country, where Arenal, Sandillal, and Corobicí Dams are located, reservoir storage appears to have only a slight impact on overall surface hydrology of the country. Again, this is consistent with the overall hypothesis that dams in the tropics do not have as large an impact on surface water hydrology as they do in temperate regions.

The third objective was to analyze discharge downstream of several dams to assess the impact that dams have at the basin scale. The working hypothesis was that the wetter climate in Costa Rica would lead to more frequent releases from dams, and therefore only a small change in downstream discharge. Four dams were chosen for this part of the study, two dams (Arenal and Sandillal) that had high impacts on hydrology within their basins based on reservoir capacity, and two dams (Corobicí and Ventanas) that had low impacting reservoir storage. Discharge data analysis of the Arenal-Corobicí-Sandillal cascading dam sequence revealed dramatic changes to streamflow. First, construction of Arenal Dam on the Arenal River completely eliminated downstream flow toward the Atlantic side of the country. The redirection of flow via piping increased flow in both the Santa Rosa River and the Magdalena River, which converge upstream of the Corobicí River (figure 13).

Typically, dam regulation decreases downstream flow (e.g. Chin and Bowman, 2005; e.g. Erskine, 1985; Ligon et al., 1995; Winemiller et al., 2005). While this was the case for Arenal River, the redirection of water has resulted in increased flow on the Pacific side of the volcanic ridge in the Corobicí River. Because the Santa Rosa River flows into the Magdalena River upstream of where Magdalena Rivers converges with the Corobicí River, increased mean flows developed immediately following closure of Arenal Dam. Mean daily, minimum, and peak discharges increased by 500%, 400%, and 300%, respectively following the closure of Arenal Dam. All of the averages dropped slightly after the closure of Corobicí and Sandillal Dams. After all dam construction was finished, mean discharge has remained at a value of 35.9 cms, 300% higher than the unregulated mean.

The findings for the Arenal-Corobicí-Sandillal cascading dam series were counter to the working hypothesis. This is attributed primarily to the engineering design associated with these dams, as opposed to their location in a tropical climate. Redirection of water from the Atlantic side of the volcanic chain toward the Pacific side, supplies water for increased hydroelectric production, as well as increased irrigation for the agriculturally dominated northwestern region of the country. Therefore, after analysis, it was concluded that these dams are not representative of typical dam design, and therefore are not good indicators of typical hydrologic impacts of dams in the tropics. Ventanas Dam, although it works in cascade with other small dams, does not have as complicated an engineering design as the previous dams, and functions more typically. Examination of discharge data downstream of Ventanas Dam was consistent with the working hypothesis that dam impacts downstream would be minimal in the tropics. The mean, minimum, and peak flows decreased only slightly following dam closure. However, analysis of precipitation over the same time period is needed prior to drawing definitive conclusions based on these results. Changes in the precipitation regime since dam closure would also explain the observed changes to the flow regime.

The flow regime changes observed downstream of Ventanas Dam differ from typical values found in temperate environments (table 6). Whereas in temperate environments, the change in mean flows is usually a decrease ranging from 0-6%, assessment downstream of Ventanas Dam showed an 11% decrease following impoundment. Additionally, minimum flows showed a slight decrease (statistically insignificant) compared to an increase ranging from 240 – 480% found in temperate studies. Furthermore, while peak flows did decrease subsequent to dam closure by 33%, this falls well below the typical decrease in temperate environments ranging from 50 – 80%. Possible explanation for the differences in results between temperate studies and this one is the purpose of the dam. Management for hydroelectric production differs from that of dams that are built primarily for flood control, which is a primary function in many temperate studies. Given these results, findings for Costa Rica are consistent with the overall hypothesis that dams in the tropics would have more diminished impacts than dams in temperate regions as a result of the high annual precipitation. However, further studies are needed to develop expected ranges of change for tropical regions.

Significance

The overall objective of this study was to understand the hydrologic impacts of dams in Costa Rica accomplished via analysis at both the large national scale and at the basin scale. Results of these analyses have shown that while overall dams are having a minimal impact on the surface water component of the hydrologic cycle based on reservoir storage, in contrast to temperate regions, at the basin scale, flow regime analysis provides a better understanding of the complexities associated with these dams. All analyses revealed changes that could not be predicted based on temperate studies. While some changes were a direct result of management for irrigation (Arenal-Corobicí-Sandillal complex), all four downstream analysis reveal the necessity for further studies of downstream changes. Channel changes resulting from streamflow alteration are expected to be different than those produced in temperate environments. This is expected because changes in streamflow analyzed in this study fell outside of predicted ranges. This is important because it implies the necessity for new theory development pertaining to dams in the tropics, separate from the existing theories that apply primarily to temperate regions.

Limitations of Study

Several limitations are evident in this study. First, determination of precipitation within Costa Rica relied on isohyetal data at a scale of 1:1,600,000. The large scale of these maps limits the accuracy of data. If these data were available at a finer resolution, accuracy of precipitation values would probably be improved. However, for the purposes of these analyses, even a percent error of +/-10% would not affect the overall results of reservoir impacts.

Second, the use of a 90-meter resolution digital elevation model to derive drainage basins introduces error into drainage basin area calculations. While this does not significantly affect the reservoir and land-use analyses, if hydrologic modeling is to be employed in the future, a 30-meter resolution digital elevation model would be preferable. Additionally, because radar was used to obtain the elevation data, some values are incorrect and reflect the elevation of the canopy rather than the ground. However, because radar can penetrate through cloud cover, it was preferable to other sources.

Land use and land cover data used for these analyses were available for one time period (National Imagery and Mapping Agency, 1997). Therefore, it is possible that land use within drainage basins containing dams may have changed since these data were published. Land use and land cover data over a variety of years would improve understanding of the dynamic within basins. Determining land use change over time since dam construction would further elucidate which dams are most at risk of increased sedimentation within reservoirs.

Last, the recent development of dams in Costa Rica, along with the rest of the tropics, limits available post-impoundment data. Because of the engineering complications associated with Arenal, Corobicí, and Sandillal Dams, Ventanas Dam was chosen as a representative Dam in Costa Rica. However, only nine years of post-impoundment discharge data were available. So while there is an obvious trend in changes evident from the available data, characterization of dam impacts in the tropics will be strengthened with a longer post-dam dataset.

Suggestions for Future Research

Future research in Costa Rica should focus on geomorphological and ecological changes on the Santa Rosa River, Magdalena River, and the Corobici River where flows have increased. Both planform and cross-sectional geometry is expected to have changed, owning to the dramatic increase in streamflow. Additionally, Arenal River, downstream of Arenal Dam should be studied. Although the stream immediately downstream is dry, it is assumed that the stream resumes farther downstream as precipitation becomes adequate to provide permanent flow. Several questions arise for Arenal River. How far downstream does the flow resume with permanent flow provided by precipitation? Does the stream ever recover fully to the pre-regulated levels? If so, how far downstream does this occur?

While geomorphologic and ecologic changes resulting from decreased downstream flow have been documented, results of increased flow regimes are lacking. This implies that future investigation on both channel adjustments and ecological changes are necessary. This would not only elucidate channel changes in Costa Rica, but would provide a baseline investigation on increased flow regime. Applications of this study may be found in the United States, where retirement of dams will lead to increased flows and the subsequent adjustment of channels and ecology.

Finally, this study serves as a step toward understanding hydrologic impacts resulting from dams in the tropics. However, more studies of downstream hydrologic changes in tropical areas are needed to develop more generalized theory. Characterization of changes downstream of dams of varying reservoir capacities, and within different drainage basin sizes will permit the development of more solid predictive power of dam impacts in the tropics.

Conclusions

In conclusion, the research presented represents a first attempt to gain an increased understanding of hydrologic impacts of dams in tropical environments. The results for the research questions posed support the overall hypothesis that dam impacts in tropical environments are diminished compared to those in temperate areas. Dam density and proportion of rainfall captured is much lower in Costa Rica than in any region in the United States. Furthermore, downstream of a representative dam flow regime changes do not fall within the expected range developed for temperate environments. Therefore, it is evident that theories developed for temperate areas including changes to hydrology, and the resulting changes to geomorphology and ecology, may not apply in tropical regions. Results of this study should serve as a step toward development of a more generalized theory of dam impacts in the tropics, which will provide a better basis for dam management and future dam development in tropical regions.

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VITA

Name: Laura Richards Laurencio

Permanent Address: Department of Geography
College of Geosciences
Texas A&M University
College Station, TX 77843

Email Address: laura@geog.tamu.edu

Education: B.S., Bioenvironmental Science, Texas A&M University, 2001
M.S., Geography, Texas A&M University, 2005

Professional Experience:

2004 – 2005 Graduate Teaching Assistant, Hydrology and Environment Laboratory, Department of Geography, Texas A&M University

2002 – 2005 Graduate Teaching Assistant, Planet Earth System Science Laboratory Department of Geography, Texas A&M University

2002 – 2003 Analysis of sediment distribution downstream of Somerville Dam, Yegua Creek, Texas. (field collection and laboratory analysis of sediment size distributions)

Professional Presentations (with published abstract):

"Understanding the impacts of dams on Texas rivers" (co-author) Presented by A. Chin at the Texas River and Reservoir Management Society meeting May 16, 2005. Waco, Texas.

"The distribution of dams in Costa Rica and their hydrologic impacts" (poster). Presented at Texas A&M University Water Week 2005. March 21-24.

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